RESPONSE OF *Andropogon gayanus* TO LIME, P, AND MICRONUTRIENTS IN A HIGHLY WEATHERED AMAZON SOIL FROM COLOMBIA

By

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A greenhouse experiment was conducted to study the effect of five levels each of lime, P, and micronutrients on dry matter production, nutrient concentrations, and nutrient uptake of *Andropogon gayanus* Kunth, and on selected soil characteristics of a low fertility, highly weathered soil from the Upper Amazon Basin in Colombia. Twenty-three experimental treatment combinations were arranged in a replicated modified central composite response surface design. Lime was applied at rates of 0, 0.5, 1, 2, and 5 meq/100 g of soil. Phosphorus was applied at rates of 0, 1/32, 1/16, 1/8, and 1/4 the P adsorption maximum as calculated by Langmuir equation, equivalent to 0, 32.5, 65, 130, and 260 ppm P. Micronutrient rates were 0, 2, 5, 10, and 20 ppm Fe, and 0, 0.5, 1, 2, and 5 ppm of Zn, Cu, B, and Mn. All the micronutrients at a given level were applied concurrently. Three harvests were made at about 57-day intervals. After the third harvest, the roots were removed for laboratory analysis.

Available P in the soil was the limiting nutrient for *A. gayanus* forage and root growth. Without application of P, severe deficiency symptoms were apparent 20 days after germination. The rate of 32.5 ppm P induced a 10-fold increase in forage dry matter compared to the no P treatments. The rate of 65 ppm P produced a 100% increase in forage yield compared to that from 32.5 ppm. No significant response to lime or micronutrients was obtained in forage or root growth. Concentration of P in the forage at levels of applied P below 130 ppm ranged from 0.07 to 0.1%, lower than 0.11% reported as the critical value of P in the tissue for *A. gayanus*. Application of P increased P concentration in the forage from 0.07 to 0.15%, and in the roots from 0.07 to 0.17% at the rates of 0 to 260 ppm of applied P, respectively. Lime increased ($P < 0.01$) Ca concentration and uptake in the forage and root system, but decreased ($P < 0.01$) Zn and Mn concentrations in the plant. No effect of lime on forage Fe concentration was detected. Manganese concentrations in the forage were approximately two times as large as those in the roots. Nutrient concentrations decreased with harvests.

Lime increased pH from 4.3 in the unlimed soil to 4.7 at the rate of 5 meq $CaCO_3$/100 g of soil, reduced exchangeable Al from about 5 to 1.3 meq/100 g of soil, and decreased Al saturation of the effective cation exchange capacity (ECEC) from 60 to 18%. No effect of levels of lime on double-acid extractable P in the soil was detected. Extractable P was only increased by application of fertilizer P. Apparent recovery of applied P ranged from 7 to 23% which was considered high due to the severe P deficiency in the unfertilized soil, but apparent recovery of Ca was low compared to the amounts applied.

INTRODUCTION

Tropical rainforests have a high productivity potential if appropriate technology based on in situ research is generated to overcome the various and complex problems that affect the establishment and productivity of crops.

Much research is now being conducted in tropical and subtropical regions but most of the questions particularly related to soils under tropical rainforests remain to be solved. Whyte (1962) cast doubt on the wisdom of clearing the jungle in order to plant crops because he believed that with the destruction of the evergreen forests, soil fertility would decline.

Whyte's theory may be applicable when the forest is cleared using heavy machinery. Clearing, if done conscientiously, with minimum disturbance of the delicate ecological equilibrium, permits economically feasible crop (Seubert et al., 1977) and cattle (Vacarro et al., 1977) production, probably without erosion problems (Lal, 1977).

Tropical rainforest soils generally have low fertility, associated with high acidity, little available P and Ca, high levels of exchangeable Al,and low cation exchange capacities (CEC). Kamprath (1970a) demonstrated that lime requirement for highly weathered mineral soils should not be based on the criterion to raise the pH of the soil to some predetermined value but, instead, it should be based on the neutralization of part of the exchangeable Al. Recent refinements in this methodology in tropical areas (Spain et al., 1975) indicates that lime may be needed at even lower rates than those recommended by Kamprath (1971). Lime should be added in sufficient quantity to supply only the Ca requirement of the plants, and probably, the use of simple superphosphate as the source of P would give the small amounts of Ca and also S required for plant growth.

As research in the tropics continues to provide data, interesting changes in recommendations are observed. Andrew and Robins (1971) in Australia reported that critical P values in the tissue for tropical grasses ranged from 0.16 to 0.25%. Falade (1975) in Nigeria indicated a critical P value of 0.19% for *Andropogon gayanus* Kunth, and Jones (1979) stated that for *A. gayanus* grown in an Oxisol in Colombia, a critical P level of 0.11% was estimated. This seems to indicate that research cannot be extrapolated from one tropical region to another, much less from temperate zones to the tropics.

The Amazon basin covers parts of six countries in South America in various proportions. In the case of Colombia, 32% of the total area of the country is located in the Amazon region, equivalent to more than 30 million ha. The population is presently very sparse but one of the functions of research is to anticipate solutions to future needs as the region develops.

The objectives of the present study were

a) To evaluate the effect of lime, P, and micronutrients on dry matter yield, plant nutrient concentrations, and mineral uptake of *Andropogon gayanus* Kunth in a soil from the Amazon Basin of Colombia;

b) To evaluate the effect of lime, P, and micronutrients on pH, double-acid extractable nutrients, and 1 N KCl exchangeable elements in the soil;

c) To estimate theoretical levels of lime, P, and micronutrients required for maximum total production of forage after three harvests of *A. gayanus*; and

d) To serve as an initial step for future research that must be conducted in the area to correlate the results of this research with on-farm responses.

LITERATURE REVIEW

Characteristics of *Andropogon gayanus*

Andropogon gayanus Kunth is a perennial rhizomatous grass capable of producing dense tussocks with culms up to 3 m tall. The species belongs to the Tribe Andropogoneae, Subfamily Panicoideae within the Family Gramineae (Bowden, 1964).

No agreement exists in the literature regarding the number of botanical varieties within the *A. gayanus* species. Foster (1962) recognized four varieties, *squamulatus* (Hochst.) Stapf, *bisquamulatus* (Hochst.) Hack., *gayanus* Hack., and *tridentatus* (Hochst.) Hack. According to Bowden (1964) *A. gayanus* is a polymorphic species which was divided by Stapf into three varieties, *gayanus* (*genuinus* Hack.), *squamulatus* (Hochst.) Stapf, and *bisquamulatus* (Hochst.) Hack. The variety recognized as *tridentatus* by Foster (1962) has been included in the var. *bisquamulatus* by Bowden (1964). Main differences between varieties are the length of the awn and presence or absence of ciliate pedicels on the margin of the leaf. Gould (1956) indicated that the basic chromosome number $n = 10$ but polyploidy is common.

The species is widely distributed through the tropical and subtropical savannas of Africa south of the Sahara desert, although some differences in distribution among varieties have been observed. Bowden (1964) indicated that *A. gayanus* var. *squamulatus* is the most widely distributed and can be found on both sides of the equator. Variety *bisquamulatus* has approximately the same distribution north of the equator but is rarely found in Africa south of the equator. Variety *gayanus* dominates large areas of seasonal flooded plains over a range similar to that of var. *bisquamulatus* but also occurs south of the equator.

As pointed out by Bowden (1963b), *A. gayanus* var. *bisquamulatus* is the most aggressive of the varieties and most of the time reference is made to this variety. Jones (1979) reported that this particular variety was the one introduced to Colombia with promising results.

The species is able to grow at low soil fertility status (Bowden, 1964; Haggar, 1975; ICA-CIAT, 1978; and Jones, 1979), probably due to the special characteristics of its root system. Bowden (1963a) described three morphological classes of roots in *A. gayanus*; fibrous, cord, and vertical roots. Fibrous roots account for about 50% of the total root weight and are responsible for horizontal exploration of the soil near the surface. Cord roots anchor the tussock and account for about 40% of the root weight. Vertical roots go deep into the soil sometimes below 0.8 m under the surface and explore for water well into the dry season.

Several reports have indicated that the nutritive value of *A. gayanus* can be classified as medium to low when compared to other tropical grasses (Haggar, 1970; Haggar and Ahmed, 1970; Haggar, 1975; ICA-CIAT, 1978; and Jones, 1979), but definitely superior to the native species found in the llanos of Colombia (ICA-CIAT, 1978 and Jones, 1979).

Regarding response to fertilization, Bowden (1963b) reported that *A. gayanus* responded to 224 kg/ha of ammonium sulfate by increasing the dry matter (DM) yield threefold in the presence of 224 kg/ha of simple superphosphate. Haggar (1970) indicated that unfertilized grass had a forage P content of 0.057% which was raised to 0.17% after the application of 448 kg/ha of ordinary superphosphate. In a later report, Haggar (1975) studied the response of this species to N in the range from 0 to 896 kg N/ha. Maximum DM yield was obtained with 500 kg N/ha with an efficiency of only 7 kg DM/kg N applied. The highest N efficiency in the experiment was estimated as 14 kg DM/kg N obtained with a rate of 28 kg N/ha.

Experiments conducted in Colombia (ICA-CIAT, 1978) indicated that *A. gayanus* has a relatively low critical value of P in the tissue (0.11%) and also in the soil (5.2 ppm extractable P, by the Bray II method). Jones (1979) reported that *A. gayanus* was compared with *Panicum maximum*, *Brachiaria decumbens*, and *Hypharrhenia rufa* on the basis of response to fertilizer P in a well-drained Oxisol. All the grasses responded up to 400 kg P_2O_5/ha. Without P, relative DM yields were 35, 0, 20, and 10% of that of the maximum, respectively. At the level of 50 kg P_2O_5/ha relative DM yields increased to 55, 38, 60, and 20% of that of the maximum, respectively. Lime was not effective in increasing DM production of *A. gayanus* and little response to Mg was obtained although good response to S was detected.

Olsen and Santos (1975) in Brazil also detected no response to application of lime on a natural pasture composed by *Andropogon lateralis*, *Paspalum notatum*, and *Desmodium spp*. unless legumes were oversown.

Soils of the Amazon Basin

The Amazon region covers about 6.75 million km^2 (Fassbender and Diaz, 1970). Brazil is the largest landholder with 5.8 million km^2 (Vieira and Bornemisza, 1968). The Peruvian Amazon represents almost 45% of the country, and in the case of Colombia, about 32% of the territory is located in the basin (Cervantes et al., 1970). Peruvian and Colombian Amazon regions are included in the Upper Amazon, as divided by Sombroek (1966).

Originally it was believed that most of the soils of tropical America under savanna and rainforest vegetation were Oxisols (Zelazny and Calhoun, 1971 and Aubert and Tavernier, 1972). Recently, Sanchez and Buol (1974) estimated that Oxisols were the most widespread soil order in the savannas but not in the rainforests where Ultisols are considered to be predominant. Lopes and Fox (1977) studied 518 topsoil samples representative of 600,000 km^2 of savannas of Central Brazil. Most of the soils were classified as Oxisols with some Entisols, Inceptisols, and a few Ultisols. The pH range of the soils was from 4.8 to 5.2, organic matter from 1.5 to 3.0%, CEC from 0.35 to 8.1 meq/100 g of soil, and a median Al saturation of 59%. With respect to Al saturation, 79% of the samples had over 40% and only 9% of the samples had an Al saturation value below 20%. Effective cation exchange capacity (ECEC) was very low. The authors indicated that extractable micronutrients may be a potential problem with cropping, especially Zn and Cu. It was found that 81% of the soil samples contained less Zn than the critical value of 0.8 μg/ml and that in 70% of the samples extractable Cu was below 7.65 μg/ml which was considered as the critical value for this micronutrient. It was concluded that Mn and Fe will probably not become problems with cropping in the near future. Soils from Carimagua Experiment Station (CIAT, 1977) in the llanos of Colombia have also been classified as Oxisols (Typic Haplustox) with 38% clay and 12% sand. Kaolinite was determined as the dominant mineral.

Flores et al. (1978) studied 11 soil profiles from the Upper Amazon region near Iquitos, Peru. Soils were classified as Ultisols and Spodosols; none of them was classified as Oxisol. Characteristics of the soils were a high sand content, low CEC, and little available K. Kaolinite was reported to be the controlling mineral at the surface in the Ultisols, and Quartz in the Spodosols.

Tyler et al. (1978) indicated that several soils from the Yurimaguas Experiment Station in the Peruvian Amazon located at 5°45' S. Lat. and 76°05' W. Long. were classified as Ultisols, the main great groups being Rhodudults, Hapludults, and Paleudults. Paleudults were found mainly on convex surfaces; they had a pH of about 4.2 and ECEC of 3.6 meq/100 g of soil. All the soils appeared to be highly weathered.

Guerrero (1975) pointed out that some variation exists regarding the classification of the soils of the Colombian Amazon. Oxisols (Typic Haplortox and Typic Gibbsiortox) are probably present and Inceptisols (Typic Eutropept, Aquic Distropept) are common. Ultisols (Aquic Paleudults) can be found in some poorly drained areas. The same author (1975) indicated that a profile from Florencia, Caqueta, classified as Udoxic Distropept showed an Al saturation greater than

60%, had a pH (H_2O) in the surface soil of 4.8, exchangeable Al 3.2 meq/100 g of soil, and an ECEC of 5.1 meq/100 g of soil. Kaolinite was the dominant mineral in the clay fraction with a proportion of more than 55% which is in agreement with the findings of Flores et al. (1978) in Brazil.

Regarding climatological characteristics, few and incomplete reports have been found. Duchaufour (1978) classified the climate of the Brazilian Amazon as humid equatorial with a tropical rainforest vegetation and a precipitation of 3000 to 4000 mm/year. Cervantes et al. (1970) reported precipitation ranges of 3000 to 5000 mm/year for the Colombian Amazon. Detailed climatological data for part of the Upper Amazon are now being collected at the Yurimaguas Experiment Station in Peru (North Carolina State University, 1978). In 1976, the first year of reported data, maximum monthly mean temperature was 31.2°C and minimum was 21.1°C. Absolute maximum and minimum recorded temperatures were 35.8 and 11.2°C, respectively. Mean relative humidity ranged from 76.8 to 89.7%. Solar radiation varied from 337 to 416 cal $cm^{-2}day^{-1}$ with an absolute maximum of 609 cal $cm^{-2}day^{-1}$. Precipitation during 1976 was 2359 mm; February and July were the driest months with less than 90 mm rainfall each, and January and October were the wettest with about 400 mm rainfall each month. In the rainiest months, at least one thunderstorm of 50 mm or more was recorded.

Liming Tropical Soils

Criteria for liming tropical soils are different from those generally used for temperate regions (Kamprath, 1972, 1973; Lathwell, 1979b). In the tropics, the estimation of lime requirement may not be done on the basis of increasing the pH of the soil to certain values, i.e., pH 6.0 to 6.5. The normally high buffering capacity of the soil and the nature of the acidity involved require that huge amounts of lime be applied to raise the pH to those values, as demonstrated in the next two studies.

Bornemisza et al. (1967), in Costa Rica, used a Latosol with an initial pH of 4.5 to study the effect of additions of 12, 24, and 36 meq lime/100 g of soil on some soil chemical characteristics. Soil pH was increased to 5.8, 6.4, and 6.8, respectively, and CEC was raised from 29.9 to 37.4 meq/100 g of soil. The authors concluded that liming at a rate of 12 meq/100 g of soil was adequate for the soil studied. In a greenhouse experiment, conducted by Almeida and Bornemisza (1977) using three Inceptisols from Costa Rica, it was estimated that lime should be applied at a rate equivalent to three times the exchangeable Al to give maximum yields.

According to Yuan (1960, 1963), Al, Fe, Mn, and probably other hydrolyzable ions on the exchange sites of the soil complex can produce acidity when hydrolyzed. Hydrogen and Al ions are the main components of soil acidity in most acid soils. Trivalent Al ions start to hydrolyze at pH (H_2O) between 4.25 and 4.75 and the hydrolysis is complete about pH (H_2O) 5.3 to 5.4. Soil pH by no means indicates the acidity of the soil and may not show the lime requirement for crop production.

Yuan (1963) and Fiskell and Zelazny (1971) established that if a soil has a pH (1 N KCl) below 5.0, exchangeable Al may be an important fraction of the effective cation exchange capacity (ECEC) of the soil.

Thomas (1960) suggested that formation of $Al(OH)_3$, $Al(OH)_2^+$, or $Al(OH)^{2+}$ can occur in Al-saturated exchangers treated with $Ca(OH)_2$ or $CaCO_3$. Tisdale and Nelson (1975) explained with a set of equations how the hydrolysis of Al may be responsible for the low pH of solutions containing Al ions and the high buffering capacity of some soils with respect to lime effects.

Kamprath (1970a, 1970b) introduced the concept that liming leached mineral soils should be done on the basis of neutralizing the exchangeable Al^{3+} of the soil instead of raising the pH to some predetermined value. Evans and Kamprath (1970) supported the concept with evidence from their work with corn and soybeans planted on mineral and organic soils. In mineral soils, Al in the soil solution was better correlated with percent Al saturation but in organic soils, the Al in the soil solution was better correlated with the exchangeable Al. A sharp increase in Al in solution occurred when the percent Al saturation was greater than 60 for the three mineral soils studied. The authors noticed a differential tolerance of plants to Al in solution; corn showed maximum growth when Al in solution was less than 0.4 meq/liter, a concentration that corresponded to a 60% to 70% Al saturation. Soybeans, in contrast, had a maximum growth at a concentration of Al in the soil solution of less than 0.2 meq/liter (about 30% Al saturation). These findings are in agreement with McLeod and Jackson (1967) who suggested that the concentration of Al in the soil solution is not directly related to the amount of exchangeable Al in the soil and neither is Al in the soil solution and soil pH.

Reeve and Sumner (1970b) evaluated the response of sorghum (*Sorghum sudanense*) to lime on the basis of neutralization of the exchangeable Al in eight Oxisols from Natal. The application of lime to reduce the soil exchangeable Al to 0.2 meq/100 g of soil was more effective and economical than the application of lime to neutralize the pH of the soil. The reaction of lime over the exchangeable Al was slow because other sources of soil acidity such as hydroxy Al and Fe, and organic matter are neutralized simultaneously. Moreover, liming mineral soils to increase the pH may lead to detrimental effects on plant growth due to nutrient imbalances or deterioration of some soil physical characteristics, as indicated by Kamprath (1971). Beneficial effects of liming have been indicated by McLean (1971).

Foster (1970) evaluated the effect of lime on micronutrients availability and found that only once out of 26 occasions was liming associated with limited uptake of micronutrients by groundnuts when trace elements were applied as foliar spray. In a total of 84 experiments, harmful effects due to overliming were clearly detected in only one.

Juo and Ballaux (1977) limed an Ultisol from Nigeria to pH 7.0 and were able to observe severe yield depression at 3 weeks but the condition tended to alleviate itself after 10 weeks.

Pearson (1975) suggested that corn yields can be increased by liming when soil pH falls below 5.0 or the Al saturation exceeds 15%. Wade and Sanchez (1976) indicated that a value of 35% Al saturation can be considered as the critical value for corn in an Ultisol in Peru. Increase in yields of *Sorghum bicolor* as a consequence of liming a Latosol with an initial pH of 4.7 was detected by Alvarez et al. (1978) in Brazil.

Amedee and Peech (1976a) questioned the validity of the use of exchangeable Al as a criterion for liming tropical soils. The authors indicated that the amount of Al (III) extracted with 1 N KCl is greater than the amount extracted from the soil in freshly precipitated $Al(OH)_3$ and gibbsite, probably because the freshly precipitated material has a larger specific surface than the amorphous $Al(OH)_3$ of the soil. They concluded that the release of Al (III) from acid tropical soils cannot be attributable to the solubility of gibbsite which is virtually insoluble in 1 N KCl.

In another report, Amedee and Peech (1976b) indicated that estimation of lime requirements by using the exchangeable Al method tends to underestimate the amount of $CaCO_3$ that should be used, and the determination of the exchangeable acidity by the $BaCl_2$-triethanolamine method would be in better agreement with the amount of $CaCO_3$ decomposed by the soil, particularly in those soils containing a high proportion of aluminous chlorite. No evidence supportive of this thesis was found in the tropical literature.

Rhodes and Lindsey (1978) equilibrated two soils from Sierra Leone with 0.01 M $CaCl_2$ using a 1:2 soil to solution ratio. It was concluded that the Al^{3+} activity in both soils was pH-dependent and the level of Al^{3+} activity was governed by dissolution of kaolinite in equilibrium with quartz.

Gallez et al. (1976) in Nigeria used several Alfisols and Ultisols to demonstrate that CEC measured by 1 N NH_4OAc at pH 7.0 and exchangeable acidity measured by 0.5 N $BaCl_2$ at pH 8.0 tended to overestimate those parameters. The authors concluded that ECEC is a better approach, thus producing evidence against the Amedee and Peech theory (1976b).

Plant Responses to Soil Acidity

Differential response of plant species to soil acidity has been detected in temperate regions and also in tropical areas. Bradshaw et al. (1958, 1960a, 1960b) compared the growth of seven grass species in nutrient solution culture at pH 4,0, 5,5, and 6.5. The authors concluded that *Nardus stricta* had better root growth at pH 4.0 than the other six temperate grass species. Foy and Brown (1964) observed that Al injury in buckwheat (*Eriogonum heracleoides*), barley (*Hordeum vulgare*), and bushbeans (*Phaseolus vulgaris*) was accompanied by a reduction in ^{32}P uptake by plant tops. The barley root system was the most affected by the Al in solution. The condition was prevented by adding a chelating agent (EDDHA) at 50% the molarity of the Al added to obtain maximum growth. The authors suggested that Al tolerance was associated with the ability of the plants to absorb P at high Al concentrations in the growth medium.

In tropical literature, similar evidence can be found. Heylar and Anderson (1971) studied the effect of lime on the growth of five grass species. Species tolerant to Al may accumulate higher P concentrations under conditions of Al toxicity than in absence of Al.

At low levels of P in the soil, grasses tend to have a higher P content than legumes. The authors also observed Al toxicity in pot experiments but not in the field although no explanation was given. After cropping, soil pH in pots was less than that in the field by about 0.8 pH units. Zantua and Blue (1971) detected marked reduction in DM yield of pangolagrass and millet but not tomato plants when soil was limed at 5 and 10 metric ton $CaCO_3$/ha.

Lotero et al. (1971) concluded that in general, little response to lime has been obtained with grasses in Colombia. *Melinis minutiflora*, *Hypharrhenia rufa*, *Axonopus scoparius*, and *Digitaria decumbens* were reported to be more tolerant to soil acidity than ryegrass (*Lolium perenne*), oats (*Avena sativa*), and elephantgrass (*Pennisetum purpureum*). Spain et al. (1975) observed that DM production of *Melinis minutiflora* in an acid Oxisol was greater than paragrass (*Brachiaria mutica*) and *Hypharrhenia rufa* when no lime was applied. Some response to lime was detected with 150 kg $CaCO_3$/ha but reduction in yields occurred at lime levels of 1 ton $CaCO_3$/ha or more. The authors suggested that only enough Ca to supply plant requirements for tropical species should be used, and that amount may be already included if simple superphosphate is used as the source of P. Jones (1979) included *A. gayanus* as one of the most acid-tolerant species in Colombia.

Pearson (1975) reviewed the work done on soil acidity and liming in the humid tropics and indicated that application of high N levels to tropical grasses using acid-forming fertilizers might lower the pH of the soil in the long run in such a way that need of lime may arise.

Fox (1979) indicated that Al saturation is a better predictor of corn yield than soil pH. In two Ultisols, corn production was 90% of that of the maximum when Al saturation reached the 12% level or lower.

Critical value of Ca for tropical grasses is lower (Loneragan and Snowball, 1969) than those reported for corn in temperate conditions (Melsted et al., 1969).

Effect of Lime on P Availability and Plant Uptake

Liming mineral soils which have a high capacity to absorb P may reduce the maximum P adsorption by the soil and increase P availability to plants (Woodruff and Kamprath, 1965).

Amarasiri and Olsen (1973) studied an acid red clay loam (Oxisol) from Colombia with 4% organic matter, 6 meq/100 g of soil exchangeable Al, and 3 ppm extractable P by $NaHCO_3$. Levels of 0, 2000, 4000, 6000, 8000, and 10,000 ppm Ca as $CaCO_3$ and 0, 35, 70, 140, and 280 ppm P were applied to determine the labile P in the soil solution after one crop of rye (*Secale cereale*), and another of *Setaria italica.* The authors concluded that liming decreased the soluble P and the labile P. Phosphorus adsorption maximum for the unlimed soil was 27.8 mg P/100 g of soil and 21.7 mg P/100 g of soil for the limed ones. Plant P content declined when lime exceeded the 4000-ppm Ca level. Dry matter yield was low at both low P levels and high Ca rates and this effect was accompanied by increased Ca concentration in the plant tissue. The authors speculated that probable stress in the organic acid content generally associated with a low plane of nutrition increased Ca and Mg plant content and depressed vegetative growth.

Evidence against the above ideas was reported by Villachica et al. (1974) who planted pangolagrass on a soil from Pucallpa, Peru. Lime requirement was estimated as 1/2 the extractable soil acidity. Phosphorus absorption by the plant increased with application of P and even more when lime was used.

Helyar and Anderson (1971), in Australia, evaluated the effect of five levels each of lime and P on an acid surface soil with a CEC of 4 to 7 meq/100 g of soil and 25% of 50% Al saturation. Two temperate grasses and three temperate legume species were used. Response to P was obtained only at the zero levels of lime and in no case was lime and superphosphate replaceable in their effects, although they did not substitute for each other.

Mendez and Kamprath (1978) in a greenhouse experiment planted *Pennisetum typhoides* cv. Gahi on six Latosols from Panama ranging in pH from 4.8 to 5.2, Al saturation from 45 to 70%, and exchangeable Al from 0.25 to 5.75 meq/100 g of soil. Addition of $CaCO_3$ at a rate of 0.75 x exch. Al neutralized 69 to 80% of the exchangeable Al. Addition of lime at 1.5 x exch. Al neutralized 79 to 97% of the exchangeable Al. The authors concluded that lime had little effect on P concentration in the tops of the plants in contrast to P rates.

Phosphorus in Tropical Regions

Phosphorus is probably the most limiting nutrient in tropical soils. In many cases little response to other nutrients can be expected without P (Reeve and Sumner, 1970a, 1970b; Helyar and Anderson, 1971; Amarasiri and Olsen, 1973; Blue, 1974; Spain et al., 1975; Sanchez, 1976; Lathwell, 1979a).

Due to the fact that in most of the highly weathered soils of the tropics kaolinite is the dominant mineral (Keng and Uehara, 1974; Sanchez and Buol, 1974; Guerrero, 1975; Flores et al., 1978); the major fraction of P for plant growth is normally associated with Al and Fe-P compounds. These forms of P have low solubility and thus may be capable of rendering P unavailable for adequate plant growth. At the same time, however, the low solubility of P prevents leaching losses that might otherwise be important. Oxisols and Ultisols usually have a high P fixation capacity (Sanchez, 1976; Atencio and Blue, 1977; North Carolina State University, 1978).

In some cases, occluded-P might also be an important fraction in tropical soils, according to Fassbender et al. (1978) who estimated that in four Ultisols in Puerto Rico occluded-P accounted for about 47% of the total P in the A horizon of the soils.

If the organic matter content of the soil is high, a good proportion of fertilizer P could be converted into organic P and will be of limited availability for plants unless transformed to inorganic forms. The effects of organic matter on nutrient availability for plants, soil pH, and exchangeable Al have been known for some time and it is widely accepted that soils with high organic matter content are conducive to better plant yields than soils with similar chemical characteristics but lower organic matter. Explanations for this may be that the organic matter is the main source of cation exchange sites in surface soils (Sawney and Norrish, 1971; Fiskell and Zelazny, 1971) or that it eliminates toxic substances in the soil (Thomas, 1975).

Bornemisza (1966) suggested that in many tropical soils the organic P fraction may constitute as much as 86% of the total P and is partially available to plants.

The mechanisms for utilization of organic P by plants are still not clear. Vancura (1964) and Bartlett and Lewis (1973) indicated that phosphatase activity at the surface of some mycorrhizal roots could catalyze the hydrolysis of organic compounds to other forms including orthophosphate, thereby increasing the supply of P to plants. This hypothesis probably has little application in the case of *Andropogon gayanus* since root-mycorrhiza association was reported as non-existent (Bowden, 1964). In this species, probably the theory of dissolution of mineral P compounds by exudation of organic acid by plant roots (Johnston and Olsen, 1972) seems to be more appropriate, although no supportive data were found.

That plants are important for the reduction of P immobilization has been demonstrated by Graeme and Boland (1978) who studied the release of ^{32}P from white clover plant residues in the presence and absence of growing oats (*Avena sativa*) at low and high P soil status in a greenhouse experiment. After 48 days, the reutilization of P from organic material was 29.3% at high P status in the presence of growing oats and only 0.6% at low P status without growing oats. The authors concluded that a high degree of P immobilization occurs only at low soil P levels without plants.

Phosphate Requirements of Plants

Intensity, quantity, and capacity are probably the most important factors controlling P supply to plants (Williams, 1967). Intensity is associated with the concentration of P in the soil solution; quantity, to the total exchangeable P; and capacity, to the buffering capacity of the soil. Capacity may also be related to the apparent diffusion coefficient of phosphate in the soil (Olsen and Watanabe, 1963).

Several methods are used to estimate the P requirement of plants in order to predict future potential response. The construction of sorption isopleths--commonly known as isotherms--to obtain a certain concentration of P in solution is widely used (Reeve and Sumner, 1970a). Other methods estimate the maximum amount of P that a particular soil is theoretically able to adsorb or "fix" under simulated circumstances (Barrow, 1978). A third method, critical tissue values, can also be used if its limitations are considered (Bates, 1971).

The methods are based on the reaction of fertilizer P with soil. This reaction is dependent on the nature and amount of adsorbing surface of the soil, pH, organic matter content, and other related factors.

Sorption isotherms and estimation of the maximum P adsorption capacity of the soil rely on the measurement of the P remaining in solution after equilibration of the soil with several solutions of known P concentrations (Olsen and Watanabe, 1957; Woodruff and Kamprath, 1965; Reeve and Sumner, 1970a). Main difference between the two methods is the mathematical approach to calculate the values. Sorption isotherms generally make use of the Freundlich equation, whereas calculation of the P adsorption maximum implies the utilization of any of the forms of the Langmuir equation, usually the linear one (Olsen and Watanabe, 1957; Woodruff and Kamprath, 1965).

Kanwar (1956) studied the phosphate retention in some Kangaroo Island soils in South Australia which had only 0.01% of total P_2O_5 but are able to fix up to 15,000 ppm PO_4. The high sorption capacity of the soil was associated with kaolinite or hydrated oxides of Al and Fe, mainly gibbsite and goethite.

A similar P adsorption maximum was reported by Weir (1972) in Jamaica for some bauxite soils. In this case, the total P contents of the soils were high, about 1972 ppm P for a red soil and 4850 ppm P for a brown one. The P adsorption maximum calculated by the linear form of the Langmuir equation was estimated as 1820 and 1280 ppm P for the red and brown bauxite soils, respectively.

Syers et al. (1973) estimated the P adsorption maximum in some soils from the state of Sao Paulo, Brazil, as 1750 μg P/g of soil for the Durox soil, a highly weathered, 800 μg P/g of soil for the Cambia soil, an intermediate weathered, and 650 μg P/g of soil for the Sao Gabriel soil, the least weathered one. The authors concluded that for tropical soils, the weathering of the soil is directly associated with its capacity to adsorb added fertilizer P. Rhodes (1977) in highly weathered soils of Sierra Leone with high P sorption values, indicated that extractable P was the main problem of the soils rather than low total P.

Rajan and Fox (1975) determined the P adsorption maximum for some tropical soils using the binary-type Langmuir equation. It was suggested that phosphate adsorption is related to increased pH and sulfate release at low levels of P adsorbed, and increased silicate release. Displacement of structural silicates and disruption of hydrous oxide polymers were associated with increased phosphate adsorption up to 50% over that of surface exchange reactions.

Munns and Fox (1976) added dissolved phosphate to three Oxisols and one Inceptisol to monitor the decline in concentration in soil solution phosphate for a 300-day period. After 50 days, an apparent steady state was reached. At this equilibrium point, they behaved as if 30 to 60% of the added phosphate remained labile. In another long-term study, Holford and Mattingly (1976a) equilibrated 24 soils with several levels of P for 2 years prior to an experiment using the binary Langmuir equation to derive a model for the equilibrium buffering capacity (EBC) of the soils as related to the intensity and quantity factors of P. The authors concluded that EBC is independent of P saturation.

Estimation of P requirements for plant growth should be based on the amount of P needed to give 95% of maximum growth (Ozanne and Shaw, 1967) or even 90% if the Mitscherlich curve is fitted to the sorption data (Ozanne et al., 1976).

Van der Zaag et al. (1979) compared available information regarding the use of sorption curves for soils in Hawaii, Bangladesh, Idaho, Ontario (Canada), and Huancayo (Peru). Potatoes were selected as the test crop. The authors estimated that a level of 0.2 ppm P in the soil solution may be used as the standard value to obtain 95% of the maximum yield of the crop regardless of location.

Holford and Mattingly (1976b) used ryegrass (*Lolium multiflorum*) as the test species in 24 temperate soils to relate the intensity, quantity, and capacity factors of the soils with plant P uptake. A low correlation ($r = 0.43$) between the adsorption capacity and the bonding energy parameter led to the conclusion that the buffer capacity of the soil may not be highly correlated with the adsorption capacity in many soils.

Harter and Baker (1977) questioned the use of the Langmuir equations for the estimation of the adsorption dynamics and bonding strength. A new equation was proposed. In this equation, the constants can be evaluated by Gauss elimination. The authors indicated that Langmuir equations can be useful to calculate the P adsorption maxima of the soils, although no report in the literature was found regarding the use of the proposed equation.

A different approach to estimate the P requirement of plants based on the Intensity-capacity factors of the soil has been proposed by Lee and Bartlett (1977). A relationship named Phosphorus Fertilizer Index (PFI) was established between the added P and the square root of the NH_4OAc-P measured after incubation. The plot of the two variables produces a straight line with a characteristic slope for the particular soil. The PFI showed a high correlation ($r = 0.94$) with extractable Al by NH_4OAc at pH 4.8 in 50 soils from the State of Vermont. The authors concluded that this approach may be used in leached soils with organically complexed reactive Al identifiable by NH_4OAc at pH 4.8. No evidence regarding the use of the PFI was found.

Response of Grasses to P Fertilization in the Tropics

Tropical soils have high variability in chemical, physical, and mineralogical characteristics (Zelazny and Calhoun, 1971; Aubert and Tavernier, 1972; Pearson, 1975; Sanchez, 1976; Lathwell, 1979a). It is not possible to treat tropical soils as a homogeneous group even in relatively small areas within a specific country or region.

Reeve and Sumner (1970a), in Natal, studied the effect of lime, gypsum, and silene (commercial product) at rates equivalent to 0, 1/2, 2/3, and 1 x lime requirement for pH 6.5 (SMP method) and two levels of P, 20 and 80 ppm, in a complete factorial experiment. Trudan (*Sorghum sudanense*) was used as the test species. Results indicated that high levels of lime decreased P availability and reduced yields probably due to a nutrient imbalance. Extractable Mn at levels of lime greater than 1/3x lime requirement for pH 6.5 were almost zero. Fixation of P was largely responsible for the differences in productivity between soils ($r = 0.83$, $P < 0.001$).

Andrew and Robins (1971), in Australia, evaluated the effect of P on the growth of nine tropical grasses in a surface soil with a pH (1:2 H_2O) of 5.9, extractable P 2.8 ppm, CEC 6 meq/100 g of soil, and extractable Ca, Mg, K, Na, and H of 1.56, 1.17, 0.04, 0.53, and 2.7 meq/100 g of soil, respectively. Among the test species, *Melinis minutiflora* was the most responsive to P. At the zero P level, *M. minutiflora* yields were only 0.02 g/pot, an amount insufficient for plant analysis. In the overall results, as DM increased, P concentration in the plant decreased. Critical concentrations of P in plants ranged from 0.16% for *Digitaria decumbens* to 0.25% for

Paspalum dilatatum. *M. minutiflora* critical P level was estimated as 0.18%. Spain et al. (1975) indicated that *M. minutiflora* in acid Oxisols is one of the least responsive species to P fertilization. According to Jones (1979), DM production of *Andropogon gayanus* and *Brachiaria decumbens* without P were 35 and 20% of that of the maxima, respectively.

Vasconcelos et al. (1975) used two Latosols from the State of Matto Grosso in the Brazilian Amazon in a greenhouse experiment to test the effect of lime and P on the growth of sorghum. Lime did not significantly affect soluble P forms and maximum yield of dry matter was obtained at a P rate equivalent to 75% the P adsorption maximum as calculated by the Langmuir equation (102 mg P/kg soil).

ICA-CIAT (1978) in the release bulletin of *Andropogon gayanus* cv. Carimagua stated a critical P value in tissue of 0.11%, well below the values reported in Australia for tropical grasses (Andrew and Robins, 1971) and in the USA for *Andropogon scoparius* (Wuenscher and Gerloff, 1971).

Falade (1975) planted *A. gayanus*, *Panicum maximum*, *Pennisetum purpureum*, and *Cynodon plectostachyus* in a pot experiment to compare six levels of P--0, 15, 30, 60, 120, and 180 mg/2 kg of soil in each pot as $Ca(H_2PO_4)_2\ H_2O$. In all the species, P concentration increased with the addition of P. Concentration of P in the plant for maximum growth of *A. gayanus* was estimated at 0.19% and maximum yield was equivalent to 174% of that of the unfertilized treatment. These results are in good overall agreement with those reported by Jones (1979) for the same species.

Vicente-Chandler (1975), in Puerto Rico, indicated strong response of *Pennisetum purpureum* to 75 kg P_2O_5/ha on an Ultisol that had received little P previously. Concentration of P in the plant increased with applied P up to 150 kg P_2O_5/ha. On a heavily fertilized soil, *P. purpureum*, *Panicum maximum*, and *Digitaria decumbens* did not respond to P.

Enwezor (1976), in Nigeria, found an inverse relationship (r = -0.70) between P sorption capacity and P availability. Aging of P in the soil for 1 to 6 months decreased responses to applied P by 6.4 to 21.3%. Lack of response to P at soil pH below 4.7 was associated with Al toxicity rather than to P fixation. Liming was effective when soil pH was less than 4.7, otherwise the effect was detrimental for corn growth.

According to Awad et al. (1976), lime or P had to be applied to increase yield of kikuyugrass (*Pennisetum clandestinum*) on a Krasnozem in Australia. Addition of P decreased Al in the soil solution and increased Ca uptake. The authors concluded that Al toxicity and Ca deficiency were interrelated.

Aluminum in the soil solution plays a most important role in the absorption of applied P by plant roots although Mn toxicity should not be overlooked (Blue and Dantzman, 1977). The efficiency of P absorption by the plant is more related to morphology and rate of growth of the root system than to the root metabolic activity (McLachlan, 1976).

Maximum growth of guineagrass on an Ultisol from Venezuela occurred at 1/2 the P adsorption maximum, equivalent to 270 ppm P, according to Atencio and Blue (1977). Triple superphosphate was more effective in increasing DM production of the grass than a locally produced (Venezuelan) rock phosphate.

Mendez and Kamprath (1978) concluded that in several Latosols from Panama, no benefit was obtained with lime application at high P levels when the Al saturation in the soil was less than 60%. When Al saturation was over 60%, large applications of P did not completely overcome the toxic effects of Al on *Pennisetum typhoides* growth.

Timing of P application is very important according to Fox and Kang (1978) who suggested that for corn, planted in an Alfisol from Nigeria, P is most effective when applied at early stages of growth.

Apparently, there is better response to initial banded than to broadcast P (Lathwell, 1979a)for corn, although in some instances broadcast P has been more successful (Yost et al., 1979). However, there is close agreement on the need of maintenance P application for long-term high crop production. Annual maintenance P rates can be as low as 20 kg P_2O_5 or as high as 60 kg P_2O_5, preferably using superphosphate (Lathwell, 1979a).

Residual Effect of P Applications in Soils

When added to soil, soluble fertilizer P is transformed to adsorbed phosphate and metastable mineral phosphate by processes of adsorption, recrystallization, and precipitation. Newly formed metastable minerals are slowly transformed into stable forms with low solubility. The decline in the residual effect of P depends on the rate of transformation of metastable forms into the stable ones and losses of P from the system.

Anderson and McLachlan (1951) recognized the notable residual effect of P on pastures and recommended that, for better annual yields, 50% of the P be applied in the first year, 25% in the second year, and the remaining 25% in the third if the total P application was over 1200 lb P/acre. If total application of P was below 800 lb/acre, a single initial application was suggested, on four acid soils in the Southern Tablelands of New South Wales.

Jackson (1966) indicated that total DM production of grasses over a 4-year period was almost entirely dependent on the amount of superphosphate applied. Frequency of application had little effect on total yield. A single initial application was as effective as more frequent dressings.

Gamboa and Blasco (1976) studied the residual effect of the application of 2 metric tons P_2O_5/ha in a soil from Costa Rica after five corn crops. The highest retention of P occurred in the top 30 cm of the soil with Al-P being the most important fraction. About 70% of applied P was converted into insoluble Fe, Al, and Ca phosphates. The authors suggested that P be applied in two applications to reduce the effect of high P fixation by the soil.

Winter and Gillman (1976) indicated that in a mixture of *Brachiaria decumbens* and *Stylosanthes guyanensis* all the P applied was recovered in the 0 to 60 cm soil layer after a 3-year period. Distribution was not affected by timing of application. In the 0 to 10 cm of topsoil, the acid extractable P increased from almost zero in the no P treatment to 40 ppm P at the 150 kg P/ha level.

High residual effect of applied phosphate has also been reported by Munns and Fox (1976). Holford and Gleeson (1976) indicated that any P added in excess of the immobilization capacity of the soil might be leached to soil depths outside the range of the roots in weakly buffered soils. That is not likely to be observed in most Oxisols and Ultisols of the tropics because of the typically highly buffered soils (Lathwell, 1979a) and the huge amounts of fertilizer P required to oversaturate the high adsorption capacity of the soils.

Plant Responses to Micronutrients

In general, micronutrient deficiencies are not commonly found in tropical soils. According to Kamprath (1971) and Drosdoff (1972), liming at high rates is likely to induce some micronutrient deficiencies, although at the present time it is rather general knowledge that little lime, if any, is needed in most tropical areas for acid-tolerant pasture species. Reeve and Sumner (1970a) detected a probable Mn deficiency in Trudan (*Sorghum sudanense*) after liming several Oxisols of Natal to pH 6.5 by the SMP method. Zantua and Blue (1971) observed reduced yields of pangolagrass (*Digitaria decumbens*) and millet (*Pennisetum typhoides*) but not tomato plants in an Entisol from Costa Rica when limed at 5 and 10 ton $CaCO_3$/ha. Reduction in yield was not due to induced Fe deficiency nor were Zn and Cu concentrations in plants below critical levels. Similar results were obtained by Juo and Ballaux (1977) in an Ultisol from Nigeria.

Heavy P applications over several years may also significantly reduce levels of available Zn, Cu, and Mn in the soil (Badanur and

Venkata Rao, 1973), although no real micronutrient deficiency was induced. Similar results in plants were reported by Wallace et al. (1978) by increasing P in the soil solution. Khan and Zende (1977) suggested that plant roots are the site for P-Zn interaction.

Critical values for micronutrients in the tropics may be different than those in temperate regions, as with P. Fernandes and Santiago (1972) analyzed 41 forage samples from the Amazon region of Brazil; a mean Cu value of 4.2 ± 1.5 ppm in the tissue was determined. No apparent deficiency symptoms were observed. Melsted et al. (1969) proposed a critical value of 5 ppm Cu for corn in Illinois. Beavington and Wright (1977) detected a good correlation between Cu in forage and EDTA-extractable Cu ($r = 0.51$, $P < 0.001$). In a pot experiment in Brazil, Alvarez et al. (1978) detected positive response to Zn in *Sorghum bicolor* DM yield. Application of B and Mo decreased yields. Soil used was a Distrophic red-yellow Latosol with an initial pH of 4.7, exchangeable Al of 0.6 meq/100 g of soil, extractable P of 2 ppm, and 46 ppm of extractable K.

A combination of high pH (7.5) and EDTA and DTPA as chelating agents allowed Halvorson and Lindsey (1977) to induce Zn deficiency in corn plants grown in nutrient solution. The authors concluded that Zn^{2+} is the only form absorbed by plant roots and only tiny concentrations are needed. A report by North Carolina State University (1978) gives some insight into the small amounts of micronutirents needed in the Amazon of Peru. Soybean yields were increased from 1.5 to 2.1 metric tons/ha with application of 2 kg Cu/ha, and from 2.1 to 2.6 metric tons/ha with 0.5 kg B/ha. At B applications greater than 0.5 kg/ha, soybean yield was depressed to 2.1 metric tons/ha.

Jones (1979), in contrast, indicated that no response to micronutrients was observed in an Oxisol of Colombia using *Andropogon gayanus* as the indicator species.

Regarding micronutrient toxicities, Mn will most likely be found as toxic for plant growth (Blue and Dantzman, 1977), particularly for top growth rather than root growth. According to Bromfield (1978), low levels of Streptomycete activity in acid soils are conducive to accumulation of manganous ions in enough quantities to become toxic to some plants.

MATERIALS AND METHODS

The soil used in this experiment was the 0.2 m surface layer of the top of a low hill at the Macagual Experiment Station near Florencia, Caquetá, Colombia, located in the Amazon Basin at 1°37' N. Lat. and 75°37' W. Long. This soil may be considered as representative of an important sector of the Colombian Amazon region close to the Andes. Altitude at the site is 400 m above sea level with an annual mean temperature of 26.5°C. Annual precipitation is about 4000 mm with two very short dry seasons in January and July.

Characterization of the soil indicated a very acid pH with low content of P, Ca, and high exchangeable Al (Table 1).

Soil was collected by personnel of the Instituto Colombiano Agropecuario (ICA) stationed at Macagual Experiment Station and sent via air freight to Gainesville.

Andropogon gayanus Kunth weeds were provided by Dr. Luis A. Leon of the International Fertilizer Development Center (IFDC) stationed in Cali, Colombia.

Preliminary Analysis

Lime Requirement

Lime requirement of the soil was calculated by incubating 100 g of air-dried soil passed through a 2-mm stainless steel screen, with

Table 1. Selected chemical characteristics of the soil used in the experiment.

pH (1:2 water)	4.3	
(1:2 1 N KCl)	3.8	
N, %	0.18	
O.M., %	3.0	
C/N	9.6	
Total P, ppm	307	
	Extractable	
	NH_4OAc (pH 7.0)	Double acid
	ppm	
P	--	3.0
K	6.0	6.0
Ca	250.0	240.0
Mg	5.2	7.1
Fe	0.1	16.6
Zn	0.28	0.23
Cu	--	0.09
Mn	--	4.2
	1 N KCl exchangeable	
	meq/100 g	
Ca	1.4	
Mg	0.7	
H	0.4	
Al	4.9	
ECEC^{+}	7.4	
CEC	12.7	

$^{+}$ECEC = Ca + Mg + H + Al (1 N KCl exch.).

0, 1, 2.5, 5, 7.5, and 10 meq of laboratory-grade $CaCO_3$/100 g of soil in glass beakers. Deionized distilled water was added to completely moisten the soil initially and each time thereafter as deemed necessary. The soil was stirred every day with a glass rod during a period of 30 days. After incubation, soil was air-dried for 2 days and pH was determined in a 1:2 soil to solution ratio in H_2O and in 1 N KCl (Table 2).

Phosphorus Requirement

Phosphorus requirement was calculated by fitting the linear form of the Langmuir equation as described by Watanabe and Olson (1957) and Woodruff and Kamprath (1965) to two sets of 1-g soil samples equilibrated with 50 ml of H_2O or 0.5 N CKl containing 0, 1, 2, 5, 10, 20, 40, 80, and 100 ppm P as KH_2PO_4.

In its linear form, the Langmuir equation can be written as:

$$y = \frac{c}{x/m} = \frac{1}{kb} + \frac{c}{b}$$

where

c = equilibrium P concentration, moles/liter

x/m = adsorbed P, mg/100 g of soil, calculated as the difference between amount of P added and that remaining in solution

$1/b$ = slope of the line

b = P adsorption maximum, mg/100 g of soil

k = constant related to the bonding energy of the soil for P

Phosphorus adsorption maximum when H_2O was used was calculated as 1042 ppm and as 1855 ppm with 0.5 N KCl. The value of 1042 ppm was

Table 2. Effect of $CaCO_3$ on soil pH and exchangeable Al after 30 days of incubation.

$CaCO_3$ added	pH (1:2)		Exch. Al
	H_2O	1 N KCl	
meq/100 g			meq/100 g
0	4.80	3.70	4.00
1.0	4.95	3.75	3.00
2.5	5.15	3.90	1.80
5.0	5.45	4.25	0.30
7.5	5.50	4.70	0.02
10.0	5.75	5.30	0.00

chosen as representative for the soil under study ($r^2 = 0.91$). Pertinent data are presented in Table 3.

Experimental Variables

Five levels of lime, P, and micronutrients were used in the experiment as presented in Table 4.

Lime levels selected were 0, 0.5, 1, 2, and 5 meq $CaCO_3$/100 g of soil. The zero level of lime was chosen to induce the minimum change in pH and exchangeable Al of the soil. The 5 meq/100 g of soil level was chosen to increase the pH of the soil to 5.4 and reduce the concentration of exchangeable Al to 0.3 meq/100 g of soil as indicated by the incubation study.

Phosphorus levels selected were 0, 1/32, 1/16, 1/8, and 1/4 of the P adsorption maximum, equivalent to 0, 32.5, 65, 130, and 260 ppm P, respectively.

Micronutrient levels were varied simultaneously and ranged from a zero level up to a very high level considering the possibility of any micronutrient deficiency that might have occurred at the highest rates of lime and/or P used in the study.

Source of Fertilizers

A list of the chemicals used as fertilizer sources is presented in Table 5. Pure grade laboratory chemicals were used in every case.

Table 3. Effect of added phosphorus on the amount of P remaining in solution after adsorption by the soil, and calculated P adsorption maxima for a highly weathered soil from the Colombian Amazon.

P added	P in solution	
	H_2O	0.1 N KCl
ppm	ppm	
0	0.025	0.0
1	0.1	0.1
2	0.3	0.15
5	1.3	0.25
10	3.8	0.75
20	10.0	3.25
40	22.5	15.0
80	57.5	47.5
100	80.0	62.5

P adsorption maximum	
	ppm
H_2O	1042
0.1 N KCl	1855

Table 4. Levels of lime, P, and micronutrients used on a soil from the Amazon basin of Colombia.

Lime levels	P levels	Micronutrient levels					Coded values
		Fe	Zn	Cu	B	Mn	
meq/100 g	ppm	-----------ppm-----------					
0	0	0	0	0	0	0	-2
0.5	32.5	2	0.5	0.5	0.5	0.5	-1
1	65	5	1	1	1	1	0
2	130	10	2	2	2	2	+1
5	260	20	5	5	5	5	+2

Table 5. Sources of fertilizer elements used in the experiment.

	Source
Lime	$CaCO_3$
N	NH_4NO_3, $NH_4H_2PO_4$
P	KH_2PO_4, $NH_4H_2PO_4$
K	KCl, KH_2PO_4
Mg	$MgSO_4 \cdot 7H_2O$
Fe	$FeSO_4 \cdot 7H_2O$
Zn	$ZnSO_4 \cdot 7H_2O$
Cu	$CuSO_4 \cdot 5H_2O$
B	H_3BO_3
Mn	$MnSO_4 \cdot H_2O$

Experimental Design and Treatment Combinations

A modified central composite response surface design was used in the experiment to fit a second degree polynomial to the data. Three factors (lime, P, and micronutrients) were studied at five levels each.

The total number of treatment combinations was 23 $(2^k + 2^k + 2k + 1)$ distributed in 8 factorial points, 8 corner points, 6 star points, and 1 center point (Table 6). Number of replications per treatment varied as indicated in the same table in order to obtain a better estimation of the error for the tests (Cochran and Cox, 1957).

Table 6. Treatment combinations coded values and number of replications used in the experiment.

Treat. No.	Treatment combinations			Reps.
	Lime	P	Micronutrients	
	--------------coded values------------			
	Factorial points 2^3 (± 1)			
1	-1	-1	-1	4
2	-1	-1	1	4
3	-1	1	-1	4
4	-1	1	1	4
5	1	-1	-1	4
6	1	-1	1	4
7	1	1	-1	4
8	1	1	1	4
	Corner points 2^3 (± 2)			
9	-2	-2	-2	6
10	-2	-2	2	6
11	-2	2	-2	6
12	-2	2	2	6
13	2	-2	-2	6
14	2	-2	2	6
15	2	2	-2	6
16	2	2	2	6
	Star points 2 x 3			
17	2	0	0	6
18	-2	0	0	6
19	0	2	0	6
20	0	-2	0	6
21	0	0	2	6
22	0	0	-2	6
	Central point 1			
23	0	0	0	12

Experimental Procedure

Liming and Incubation

The air-dried soil was screened through a 5-mm stainless steel screen and mixed with the appropriate amounts of $CaCO_3$ in a mixer-blender for 10 minutes. Then 1.8 kg of soil plus the lime added were placed in plastic pots filled with 1.3 kg of washed gravel. Pots were placed in the greenhouse, watered with distilled water to near field capacity initially, and covered with a plastic to reduce evaporation losses. Every 7 days the pots were watered to field capacity with distilled water. At the end of 30 days, it was assumed that most of the changes in soil pH and exchangeable Al had taken place, and planting and fertilization were initiated.

Planting and Fertilization

After incubation, the soil in the pots was left to dry before planting. About 10 to 15 seeds of *Andropogon gayanus* Kunth were sown in each pot at 0.5-cm depth, and then the P and micronutrient solutions were applied (10 ml of each solution) to the soils. The pots were distributed in the greenhouse and divided in three blocks according to gradients of temperature and radiation.

Five days after germination, plant population was thinned to three plants/pot. Ten days after thinning, a nutrient solution containing 100 ppm N as NH_4NO_3, 50 ppm K as KCl, and 25 ppm Mg as $MgSO_4$ was applied to all the pots by pipetting 10 ml of the solution directly to the soil.

Greenhouse Procedure

Pots were inspected daily and watered to near field capacity. Later in the growing season, it was necessary to water the plants twice a day because of the high transpiration rates. Greenhouse temperature was set between 36° and 24°C.

To control red spider infestations that occurred towards the middle of each growth period, the plants were sprayed with Kelthane (1,1-bis-(P-Chlorophenyl 1)-2,2,2-Trichloroethanol) at a dose of 5 ml dissolved in 5 liters of distilled water.

Harvests and Preparation of the Plant Material

The grass was harvested three times. The first harvest was made 57 days after planting, with subsequent harvests after 59 and 56 days of regrowth. High variability was observed in growth due to treatment effects, but most of the plants were well into the flowering stage at harvest.

Plant tops were cut at a height of 1.0 to 1.5 cm with a pair of sharp scissors. Ten days after the first and second harvests, a basal nutrient solution containing N and K was applied to all soils.

After the third harvest, the stubble-root system was promptly removed from the soil, and washed thoroughly with tap water and then with distilled water.

Plant material after each harvest and the stubble-root mass were placed in paper bags and dried at 70°C for 3 to 4 days until constant weight. Plant material was then weighed to the closest 0.1 g if weight was greater than 1 g, or on an analytical balance. In the first case, all plant material was ground in a Wiley mill to pass a 20-mesh stainless steel screen and placed into small paper bags for laboratory analysis. When material was less than 2 g, a pair of stainless steel scissors was used to cut the material into small pieces instead of grinding in the Wiley mill. Cut material was then placed in small paper bags, as indicated above, for laboratory analysis.

Preparation of the Soil for Laboratory Analysis

Soil was still moist when the stubble-root mass was removed, so it was screened through a 5-mm stainless steel screen and placed in double-strength paper bags to let it air-dry in the greenhouse for several days.

After 2 weeks, the soil from each paper bag was thoroughly mixed; a sample of about 200 g was passed through a 2-mm stainless steel screen, with the help of a large rubber stopper, and placed into a small paper bag for laboratory analysis.

Forage and Root Analysis

Ground or finely cut material was taken into the laboratory and placed in an oven for 12 hours at 70°C. From this material, a 2-g sample was weighed for ashing at 450°C in a muffle furnace for 4 to 6 hours or overnight. When little material was available, composite samples obtained by pooling the various replications were ashed. The ash was cooled before adding 20 ml of 5 N HCl. Solutions were evaporated to dryness at low temperature and then heated at a high temperature on a hot plate to dehydrate the silica. Residues were dissolved with 2.25 ml 5 N HCl, brought to a 20 ml volume with distilled water, and heated to boiling on a hot plate until amber color. The solutions were then filtered through a No. 41 Whatman filter paper into 50-ml volumetric flasks. They were taken to volume with distilled water, and transferred to 60-ml plastic bottles for storage.

Phosphorus was determined by the aminonaphtholsulphonic acid-reduced molybdophosphoric blue method as described by Fiske and Subbarow (1925). Calcium, Mg, Fe, Zn, Cu, and Mn were determined by atomic absorption spectrophotometry. Potassium was determined by flame spectrophotometry.

Soil Analysis

Soil samples taken initially and after the experiment were analyzed for pH in a 1:2 soil to solution ratio in H_2O and 1 N KCl using a Fisher Accumet, Model 320 pH-Meter. Double-acid solution (0.05 N HCl + 0.025 N H_2SO_4) was used to extract P, Ca, K, Mg, Fe, Zn, Cu, and Mn (Mehlich, 1953). Phosphorus was determined by the ascorbic acid method (Watanabe and Olsen, 1965). Calcium, K, Mg, Fe, Zn, and Mn were determined as previously described for plant material. Total acidity was determined by leaching soil samples with 1 N KCl and titrating the leachates with 0.0198 N NaOH. The same solutions were used to determine exchangeable Al by back titration with 0.0286 N HCl after addition of 10 ml of 4% NaF. Exchangeable H was calculated as the difference between total acidity and exchangeable Al (McLean, 1965). Exchangeable Ca and Mg were determined in the 1 N KCl solutions by atomic absorption spectrophotometry. Effective cation exchange capacity (ECEC) was the sum of exchangeable Al, H, Ca, and Mg. Percent Al saturation was calculated as a fraction of the ECEC.

Statistical Analysis

The GLM procedure of the Statistical Analysis System (SAS package) was used to fit second degree polynomials to the plant and soil data (Barr et al., 1976). After several runs, it was decided that the log base 10 transformation of the applied P rates would give a better prediction model than the true levels of P (Mead and Pike, 1975). Values of P of 0 ppm were approximated to one in order to obtain a logarithm value equal to zero. It was considered that the difference in response to addition of P between the level 0 and 1 ppm P would have been negligible. Once the model was selected, the terms with significance less than 10% were dropped to produce a reduced model with the most significant effects and interactions.

Contours of predicted values were plotted using the Gould Plotter Package coupled with a Fortran IV G Level program.

RESULTS AND DISCUSSION

Effect of Lime, P, and Micronutrients on Some Soil Chemical Characteristics

Effects of added $CaCO_3$ and P on soil pH in H_2O and 1 N KCl (1:2 soil to solution ratio) after three harvests of *Andropogon gayanus* Kunth are summarized in Table 7. Soil pH after cropping was lower than expected from the incubation study (Table 2), probably due to the pH-reducing effect of the neutral salts added as sources of N and K, as previously indicated by Yuan (1960), and also to the effect of relatively high absorption of Ca by *A. gayanus* roots confined in the small pot environment.

The effects of lime, P, and micronutrients as indicated by their significance levels on selected soil characteristics are presented in Appendix Table 1. Increasing levels of lime increased ($P < 0.01$) soil pH. The overall effect of P on soil pH was negative ($P < 0.01$) although a positive L x P interaction ($P < 0.01$) was estimated. Micronutrients were without effect on soil pH. The negative overall effect of fertilizer P on soil pH may have been associated with increased DM production, and consequently, with increased Ca uptake by the plants. Effects of P and Ca can be visualized in Fig. 1.

Application of lime depressed ($P < 0.01$) exchangeable Al levels in the soil as usually reported in the literature (Kamprath, 1970; Reeve and Sumner, 1970b), but P tended to counteract that effect

Table 7. Effects of $CaCO_3$ and P on pH in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	---pH (H_2O)---				
0	4.45	--	4.17	--	4.25
0.5	--	4.36	--	4.20	--
1.0	4.57	--	4.22	--	4.42
2.0	--	4.48	--	4.31	--
5.0	4.62	--	4.61	--	4.72
	---pH (KCl)---				
0	3.77	--	3.67	--	3.61
0.5	--	3.77	--	3.69	--
1.0	3.85	--	3.69	--	3.65
2.0	--	3.84	--	3.76	--
5.0	4.03	--	3.97	--	3.94

$$Z = 4.4586 - 0.2271\text{Log } P + 0.0506(\text{Log } P)^2 + 0.023L + 0.00234L^2 + 0.0275(\text{Log } P)L$$

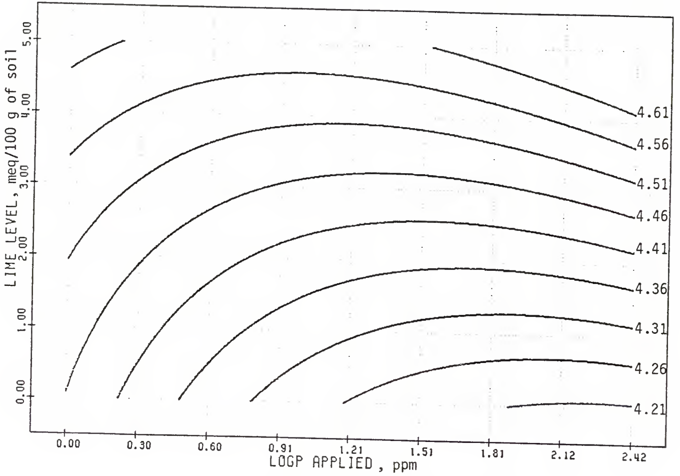

Figure 1. Contours of pH (H_2O) in the soil as affected by lime and P.

($P < 0.01$) according to data in Table 8 and Appendix Table 1. The somewhat unusual effect of P on increasing exchangeable Al in some soils is known but does not occur widely (M.E. Sumner, 1979, personal communication). That some Al^{3+} activity remained in the soil, even after lime application at a rate of 5 meq/100 g of soil, is emphasized by the large difference between soil pH values in H_2O and KCl (Yuan, 1963). Contours of predicted Al saturation values at various P and Ca rates are presented in Fig. 2.

Lime and P increased ($P < 0.01$) the effective cation exchange capacity (ECEC) of the soil (Table 9 and Appendix Table 1). Most of the effect of lime was probably due to the displacement of Al polymers from the exchange complex of the soil. Saturation of the ECEC with Al (Table 11), as expected, was inversely associated ($P < 0.01$) with levels of lime. Effects of levels of P and Ca on ECEC appear in Fig. 3, and effects of P and Ca on percent Al saturation are presented in Fig. 4. Not all the exchangeable Al was neutralized at the highest rate of lime (5 meq/100 g of soil), perhaps because not all the lime had fully reacted with the soil. Levels of exchangeable Ca in the soil were increased ($P < 0.01$) by lime application and depressed ($P < 0.01$) by the linear effect of P but highly increased ($P < 0.01$) by the L x P interaction (Table 10 and Appendix Table 1). The effect of P on exchangeable Ca was related to increased DM production and Ca uptake by the grass.

Effects of lime and P on double-acid extractable P, Ca, K, and Mg are summarized in Tables 12, 13, 14, and 15. The levels of significance of lime, P, and micronutrients on extractable P, Ca, K, and Mg in the soil are included in Appendix Table 1. Lime increased

Table 8. Effects of $CaCO_3$ and P on exchangeable Al (1 N KCl) in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Exch. Al, meq/100 g------------				
0	3.31	--	4.96	--	4.94
0.5	--	3.48	--	4.72	--
1.0	2.83	--	4.36	--	4.53
2.0	--	2.63	--	3.51	--
5.0	1.17	--	1.36	--	1.56

Table 9. Effects of $CaCO_3$ and P on ECEC in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	--------------ECEC, meq/100 g--------------				
0	6.0	--	7.7	--	7.6
0.5	--	6.4	--	7.5	--
1.0	6.1	--	7.6	--	7.7
2.0	--	6.6	--	7.3	--
5.0	7.1	--	7.6	--	7.7

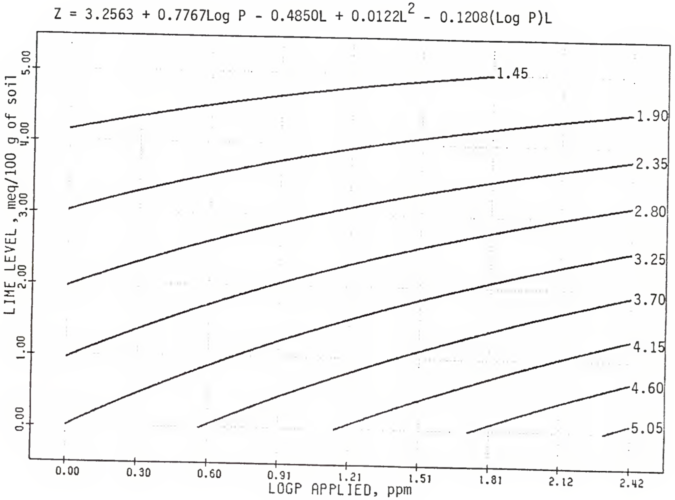

Figure 2. Contours of exchangeable Al (meq/100 g of soil) as affected by lime and P.

Table 10. Effects of $CaCO_3$ and P on exchangeable Ca (1 N KCl) in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Exch. Ca, meq/100 g------------				
0	1.12	--	1.13	--	1.13
0.5	--	1.55	--	1.53	--
1.0	1.93	--	1.97	--	2.00
2.0	--	2.71	--	2.76	--
5.0	4.94	--	5.25	--	5.42

Table 11. Effects of $CaCO_3$ and P on Al saturation in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Al sat. of ECEC, %-------------				
0	54.7	--	64.4	--	64.4
0.5	--	54.0	--	62.7	--
1.0	46.4	--	57.1	--	58.5
2.0	--	39.5	--	48.0	--
5.0	16.4	--	17.9	--	20.1

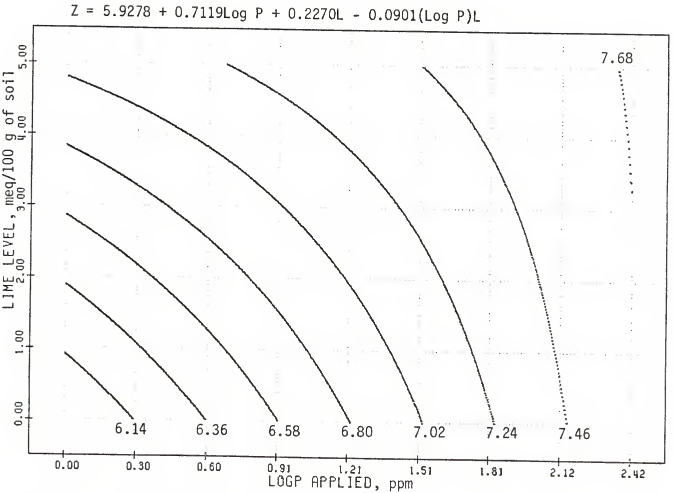

Figure 3. Contours of effective cation exchange capacity (ECEC, meq/100 g of soil) as affected by lime and P.

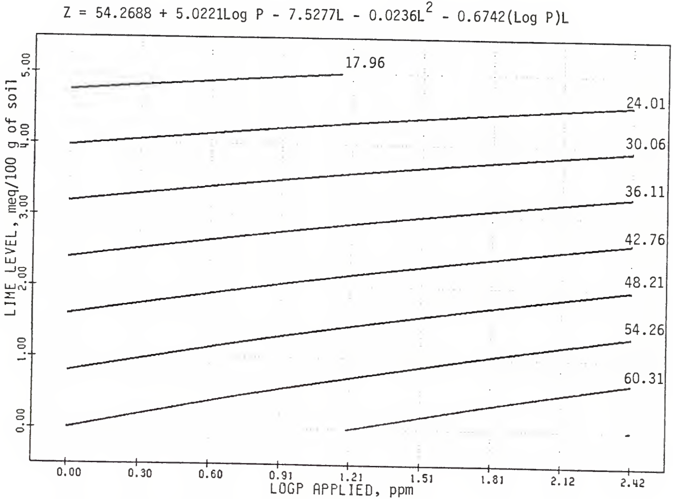

Figure 4. Contours of Al saturation (%) in the soil as affected by lime and P.

Table 12. Effects of $CaCO_3$ and P on extractable P in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Ext. P, ppm+				
0	3.6	--	6.9	--	26.2
0.5	--	5.4	--	13.1	--
1.0	3.6	--	8.4	--	24.1
2.0	--	5.1	--	13.4	--
5.0	3.6	--	6.6	--	23.4

+Ext. by 0.05 N HCl + 0.025 N H_2SO_4.

Table 13. Effects of $CaCO_3$ and P on extractable Ca in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Ext. Ca, ppm+				
0	173	--	175	--	164
0.5	--	278	--	268	--
1.0	263	--	278	--	261
2.0	--	475	--	454	--
5.0	725	--	748	--	731

+Ext. by 0.05 N HCl + 0.025 N H_2SO_4.

Table 14. Effects of $CaCO_3$ and P on extractable K in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Ext. K, ppm+				
0	103	--	16	--	18
0.5	--	44	--	19	--
1.0	91	--	15	--	18
2.0	--	40	--	22	--
5.0	97	--	17	--	20

+Ext. by 0.05 N HCl + 0.025 N H_2SO_4.

Table 15. Effects of $CaCO_3$ and P on extractable Mg in a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Ext. Mg, ppm+				
0	39	--	41	--	40
0.5	--	36	--	41	--
1.0	47	--	35	--	25
2.0	--	55	--	39	--
5.0	46	--	40	--	46

+Ext. by 0.05 N HCl + 0.025 N H_2SO_4.

($P < 0.01$) double-acid extractable K, Ca, and Mg in the soil, but it had little effect on extractable P. Double-acid extractable P in the soil was increased ($P < 0.01$) only by increasing levels of fertilizer P. Micronutrients did not show any effect ($P > 0.05$) on levels of extractable P, K, Ca, and Mg in the soil. Application of P tended to reduce ($P < 0.01$) the level of extractable K in the soil, probably because of the high absorption of K as a consequence of increased DM production by *A. gayanus* in response to fertilizer P.

Dry Matter Production

Forage Yields

Andropogon gayanus dry matter (DM) production was limited by the low level of available P (3 ppm double-acid extractable) in the soil prior to the experiment (Table 1). Forage DM production varied with harvests (Table 16). Phosphorus consistently increased DM production ($P < 0.01$) independently of lime and micronutrient levels used (Appendix Table 2).

At the 0 ppm applied P level, plant growth was stunted with P deficiency symptoms visually recognizable as purple leaves, brittle stems, and early shattering of the leaves. Most of the plants at this P level were affected regardless of lime and/or micronutrient treatment combinations used. The complete set of six replicates in the treatment combination -2, -2, 2 (no lime, no P, and highest micronutrient rate) started to die back after the first harvest as the effect of severe P deficiency probably coupled with a non-determined problem (perhaps a micronutrient toxicity). At the time of the second

Table 16. Effects of $CaCO_3$ and P on *A. gayanus* forage dry matter yield from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	----------Oven-dry forage, g/pot-----------				
			First Harvest		
0	0.05	--	6.8	--	7.1
0.5	--	2.9	--	7.1	--
1.0	0.05	--	6.6	--	7.5
2.0	--	3.2	--	6.7	--
5.0	0.08	--	6.7	--	6.6
			Second Harvest		
0	0.06	--	6.2	--	11.1
0.5	--	4.2	--	10.5	--
1.0	0.11	--	8.7	--	11.0
2.0	--	4.0	--	10.0	--
5.0	0.18	--	8.9	--	9.9
			Third Harvest		
0	0.55	--	6.7	--	10.3
0.5	--	3.7	--	8.9	--
1.0	0.90	--	7.1	--	10.7
2.0	--	4.6	--	9.2	--
5.0	1.65	--	7.1	--	10.1
			Total		
0	0.76	--	19.7	--	28.5
0.5	--	10.8	--	26.5	--
1.0	1.06	--	22.3	--	29.2
2.0	--	11.9	--	25.8	--
5.0	1.92	--	21.2	--	26.7

harvest, only three of the pots had live plants, and at the third harvest, no plants remained alive in any of the pots. In all treatment combinations that included the 0 ppm P level, plant growth was relatively normal until the low P reserve in the small *A. gayanus* seeds was depleted. Thereafter, no new growth occurred, and at 20 days after germination, plants were less healthy than before.

No effect ($P > 0.05$) of increasing levels of lime and micronutrients at any of the three harvests was detected (Appendix Table 2). Little response of *A. gayanus* to lime had been previously reported (ICA-CIAT, 1978; Jones, 1979) and these data support their conclusions. These data support Lotero et al. (1971) and Spain et al. (1975) considerations regarding effects of lime on DM production of acid-tolerant grass species in Colombia.

A similar trend was apparent when the total forage DM production for the three harvests was considered (Table 16 and Appendix Table 2). The largest increase in total forage DM yield occurred at the first increment of P applied (32.5 ppm P) with a 10-fold increase in DM production. The rate of 65 ppm P applied gave a 100% forage increase compared to the 32.5 ppm P rate. Response to P tended to proceed at a diminishing rate with increasing levels of P approaching an apparent asymptotic relationship.

Root Yields

As in the case of forage DM production, fertilizer P was the determining factor in the response of root DM weight (Table 17 and

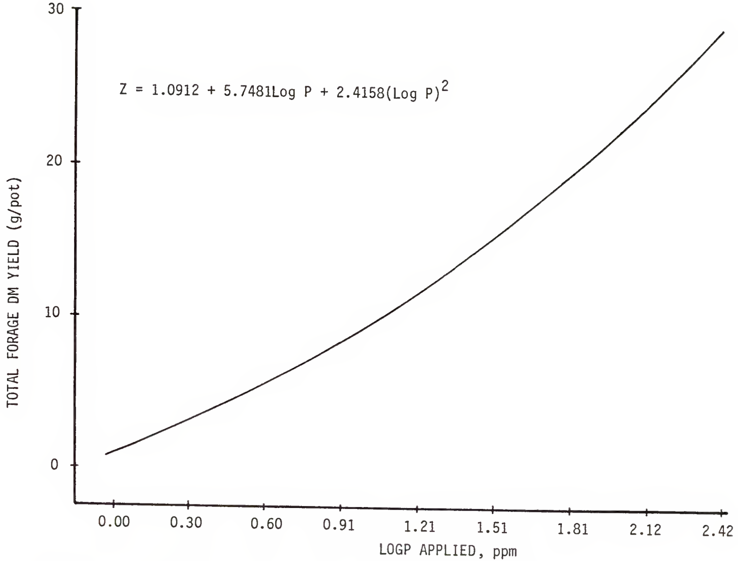

Figure 5. Response of *A. gayanus* total forage DM as affected by P.

Appendix Table 2). Lime increased root DM production when applied at rates below 2 meq $CaCO_3$/100 g of soil in combination with P through the 130 ppm rate. Lime applied at larger rates depressed root growth. Applied P significantly increased ($P < 0.01$) root DM yields although the interaction lime x P had a negative effect ($P < 0.01$) probably due to the same detrimental effects of high lime rates on DM production already reported for the forage (Appendix Table 2). Response to applied P can be seen in Fig. 6.

In every case, applied P increased root DM weight regardless of the levels of lime or micronutrients applied. However, at the 0 meq $CaCO_3$/100 g of soil level of lime, the increment in root DM yield due to P applications was notably superior to any other level of lime used (Table 17).

No significant overall effects of lime or micronutrients on root weight was detected. Without P, root DM yield was almost nil and many plants died early. At the time of root removal from the pots, all the material had decomposed beyond recognition.

Forage Nutrient Concentrations and Uptake

Nutrient concentration responses of *A. gayanus* to applied lime, P, and micronutrients were not consistent over time. Some nutrients, namely P, K, and Mg tended to be at their highest concentrations at the first harvest, and at their lowest at the third (Tables 18-29) probably because of the capacity of the plants to increase their absorption of some nutrients to excessive levels, especially at deficient P status in the soil. In the case of P, concentration of forage P was

Table 17. Effects of $CaCO_3$ and P on *A. gayanus* root dry matter yield from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-----------Oven-dry roots, g/pot-----------				
0	0.5	--	10.8	--	17.1
0.5	--	7.3	--	16.0	--
1.0	1.0	--	12.8	--	16.6
2.0	--	8.2	--	16.8	--
5.0	1.0	--	11.3	--	13.7

$$Z = 0.0222 + 2.542\text{Log } P + 1.9556(\text{Log } P)^2 + 2.288L - 0.4164L^2 - 0.3582(\text{Log } P \times L)$$

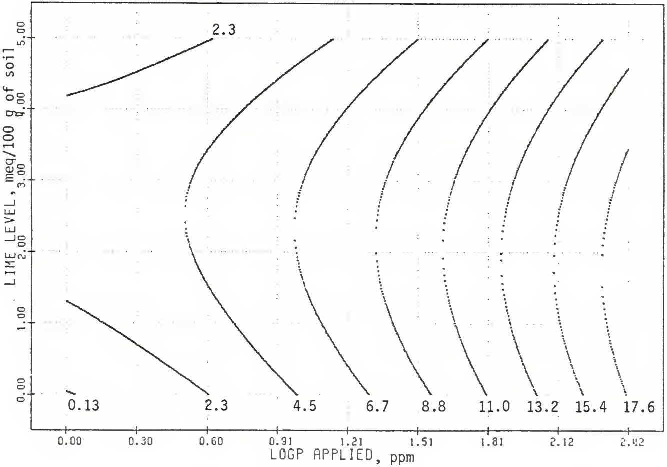

Figure 6. Contours of predicted root DM yields (g/pot) of *A. gayanus* as affected by lime and P.

decreasing after the first harvest probably due to a gradual reduction in P availability.

Calcium concentration in the forage tended to be quite similar at all harvests (Table 19) with the exception of the lowest rate of applied P in the first and second harvests when very high Ca concentrations were obtained. This may have been a consequence of impaired growth because of a severe P deficiency, or that the small amount of DM produced may also have induced some errors in laboratory determinations due to the high dilution factors involved in the calculations, or to increased Ca absorption by the plant as a protective biological mechanism. Contours of the effect of P and Ca on forage Ca concentration in the third harvest are presented in Fig. 7.

Concentrations of P in forage from the second and third harvests were lower than the value of 0.11% P at levels of fertilizer P applied at or below 130 ppm. This was the critical value reported by Jones (1979) for *A. gayanus* in an Oxisol of Colombia. In the present experiment, the critical value of P is estimated to be about 0.07% provided that enough available P remains in the soil for adequate plant growth. Probably the concentration of P in the forage is not a good parameter to predict *A. gayanus* response to fertilizer P because of the small difference in forage-P concentrations between widely different rates of P applied.

Since no effect of lime on forage P concentration was detected, our data do not support Foy and Brown (1964) and Helyar and Anderson (1971) theory regarding the increased P concentration in plant tissue at high levels of exchangeable Al in the soil, probably because of the extraordinary tolerance of *A. gayanus* to high levels of exchangeable Al in the soil.

Table 18. Effects of $CaCO_3$ and P on *A. gayanus* forage-P concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Oven-dry forage P, %				
			First Harvest		
0	0.07	--	0.18	--	0.41
0.5	--	0.21	--	0.26	--
1.0	0.07	--	0.19	--	0.45
2.0	--	0.19	--	0.27	--
5.0	0.08	--	0.20	--	0.43
			Second Harvest		
0	0.09	--	0.06	--	0.14
0.5	--	0.07	--	0.09	--
1.0	0.13	--	0.07	--	0.17
2.0	--	0.07	--	0.10	--
5.0	0.11	--	0.07	--	0.17
			Third Harvest		
0	0.07	--	0.07	--	0.12
0.5	--	0.06	--	0.09	--
1.0	0.09	--	0.06	--	0.15
2.0	--	0.06	--	0.09	--
5.0	0.08	--	0.07	--	0.15

Table 19. Effects of $CaCO_3$ and P on *A. gayanus* forage-Ca concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-----------Oven-dry forage Ca, %-----------				
			First Harvest		
0	0.39	--	0.25	--	0.24
0.5	--	0.29	--	0.30	--
1.0	0.50	--	0.32	--	0.34
2.0	--	0.42	--	0.41	--
5.0	0.83	--	0.55	--	0.47
			Second Harvest		
0	0.40	--	0.27	--	0.31
0.5	--	0.31	--	0.34	--
1.0	0.24	--	0.36	--	0.37
2.0	--	0.40	--	0.42	--
5.0	0.86	--	0.63	--	0.57
			Third Harvest		
0	0.18	--	0.27	--	0.31
0.5	--	0.36	--	0.34	--
1.0	0.21	--	0.40	--	0.37
2.0	--	0.41	--	0.42	--
5.0	0.43	--	0.63	--	0.57

$$A = 0.1668 + 0.1802\text{Log } P - 0.0503(\text{Log } P)^2 + 0.0538L - 0.0001L^2$$

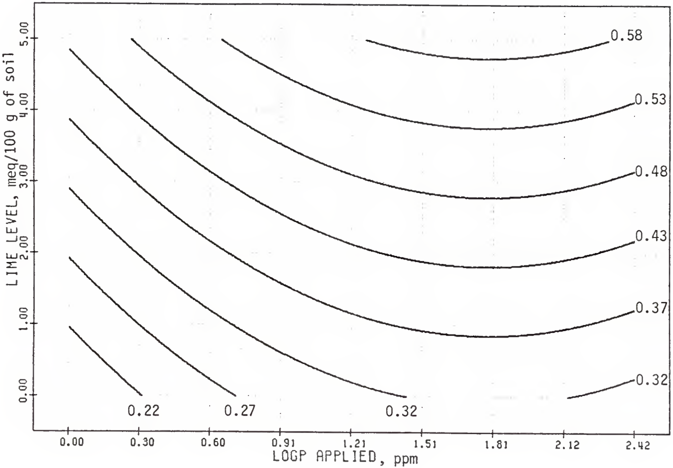

Figure 7. Contours of predicted forage Ca concentration (%) of *A. gayanus* in the third harvest as affected by lime and P.

Application of fertilizer P significantly increased forage P and Mg concentrations at each harvest ($P < 0.01$), and reduced the concentrations of Ca, Fe, Cu, and Mn ($P < 0.01$) as an effect of increased DM production (Tables 18, 20, 21, 22, 26, 27, 28, and 29, and Appendix Tables 3, 4, and 5).

Concentration of Fe in the forage was highest at the 0 ppm P level as in the case of Ca (Table 22). It was inversely related to level of lime applied ($P < 0.01$) and directly dependent on the micronutrient level in the first harvest (Appendix Table 3). In the second harvest, concentration of Fe in the forage was only inversely related to applied P (Appendix Table 4), but at the third harvest, no fertilizer treatment main effect was found to be significant (Appendix Table 5). Probably lime was responsible for the reduction of Fe activity in the soil, possibly depressing, although not significantly, the concentration of Fe in the plant. The negative effect of P on forage Fe concentration may have been attributable to increased DM production.

Application of $CaCO_3$ and P tended to lower the concentration of Zn in the forage (Tables 23, 24, and 25), and increasing levels of micronutrients were associated with increased levels of Zn ($P < 0.01$) in the grass at each harvest (Appendix Tables 3, 4, and 5).

Phosphorus significantly depressed ($P < 0.01$) Cu levels in the forage in the first harvest (Table 26), but not from later harvests (Appendix Tables 3, 4, and 5). Copper applications increased ($P < 0.01$) concentration of Cu in the forage. Overall Mn concentration in the forage was inversely related ($P < 0.01$) to lime and P applications, but surprisingly, it was quite independent of the level of micronutrients applied (Tables 27, 28, and 29, and Appendix Tables 3, 4, and 5). Effects of

Table 20. Effects of $CaCO_3$ and P on *A. gayanus* forage-K concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Oven-dry forage K, %				
			First Harvest		
0	1.54	--	2.04	--	1.70
0.5	--	2.42	--	1.85	--
1.0	1.36	--	2.02	--	1.50
2.0	--	2.52	--	1.85	--
5.0	1.50	--	2.02	--	1.70
			Second Harvest		
0	1.77	--	1.24	--	0.90
0.5	--	1.52	--	0.91	--
1.0	1.97	--	1.00	--	0.98
2.0	--	1.47	--	0.99	--
5.0	1.50	--	1.14	--	0.99
			Third Harvest		
0	1.62	--	1.12	--	0.73
0.5	--	1.29	--	0.78	--
1.0	1.72	--	0.88	--	0.72
2.0	--	1.30	--	0.78	--
5.0	1.80	--	0.93	--	0.72

Table 21. Effects of $CaCO_3$ and P on *A. gayanus* forage-Mg concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-----------Oven-dry forage Mg, %-----------				
			First Harvest		
0	0.23	--	0.25	--	0.29
0.5	--	0.22	--	0.29	--
1.0	0.20	--	0.25	--	0.31
2.0	--	0.21	--	0.30	--
5.0	0.24	--	0.23	--	0.24
			Second Harvest		
0	0.24	--	0.22	--	0.30
0.5	--	0.19	--	0.31	--
1.0	0.14	--	0.27	--	0.30
2.0	--	0.18	--	0.32	--
5.0	0.16	--	0.20	--	0.25
			Third Harvest		
0	0.19	--	0.17	--	0.24
0.5	--	0.17	--	0.23	--
1.0	0.13	--	0.23	--	0.24
2.0	--	0.16	--	0.24	--
5.0	0.10	--	0.18	--	0.22

Table 22. Effects of Fe and P on *A. gayanus* forage-Fe concentration from a highly weathered soil from the Colombian Amazon.

Fe applied	P applied, ppm				
	0	32.5	65	130	260
ppm	----------Oven-dry forage Fe, ppm----------				
			First Harvest		
0	323	--	161	--	176
0.5	--	157	--	157	--
1.0	399	--	147	--	159
2.0	--	179	--	139	--
5.0	373	--	137	--	162
			Second Harvest		
0	212	--	86	--	120
0.5	--	124	--	114	--
1.0	106	--	129	--	102
2.0	--	225	--	101	--
5.0	308	--	109	--	103
			Third Harvest		
0	216	--	145	--	188
0.5	--	254	--	192	--
1.0	--	--	190	--	79
2.0	--	148	--	161	--
5.0	258	--	218	--	212

Table 23. Effects of Zn and $CaCO_3$ on *A. gayanus* forage-Zn concentration from a highly weathered soil from the Colombian Amazon.

Zn applied	$CaCO_3$ applied, meq/100 g				
	0	0.5	1	2	5
ppm	----------Oven-dry forage Zn, ppm----------				
			First Harvest		
0	50	--	27	--	31
0.5	--	33	--	29	--
1.0	40	--	38	--	25
2.0	--	45	--	40	--
5.0	105	--	48	--	57
			Second Harvest		
0	103	--	33	--	39
0.5	--	36	--	29	--
1.0	43	--	43	--	--
2.0	--	44	--	41	--
5.0	62	--	70	--	73
			Third Harvest		
0	38	--	24	--	26
0.5	--	28	--	27	--
1.0	29	--	34	--	25
2.0	--	33	--	32	--
5.0	50	--	42	--	47

Table 24. Effects of Zn and P on *A. gayanus* forage-Zn concentration from a highly weathered soil from the Colombian Amazon.

Zn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Oven-dry forage Zn, ppm				
			First Harvest		
0	52	--	27	--	29
0.5	--	34	--	29	--
1.0	53	--	35	--	30
2.0	--	48	--	37	--
5.0	123	--	48	--	39
			Second Harvest		
0	111	--	33	--	31
0.5	--	31	--	34	--
1.0	51	--	40	--	37
2.0	--	39	--	46	--
5.0	103	--	70	--	84
			Third Harvest		
0	38	--	24	--	26
0.5	--	27	--	29	--
1.0	32	--	32	--	33
2.0	--	31	--	35	--
5.0	57	--	42	--	44

Table 25. Effects of $CaCO_3$ and P on *A. gayanus* forage-Zn concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	----------Oven-dry forage Zn, ppm----------				
			First Harvest		
0	116	--	40	--	39
0.5	--	45	--	34	--
1.0	53	--	37	--	30
2.0	--	37	--	32	--
5.0	59	--	48	--	29
			Second Harvest		
0	168	--	43	--	50
0.5	--	36	--	44	--
1.0	51	--	46	--	37
2.0	--	34	--	36	--
5.0	78	--	25	--	33
			Third Harvest		
0	48	--	29	--	39
0.5	--	30	--	32	--
1.0	32	--	34	--	33
2.0	--	28	--	32	--
5.0	43	--	25	--	31

Table 26. Effects of Cu and P on *A. gayanus* forage-Cu concentration from a highly weathered soil from the Colombian Amazon.

Cu applied	P applied, ppm				
	0	32.5	65	130	260
ppm	----------Oven-dry forage Cu, ppm----------				
			First Harvest		
0	7.0	--	7.7	--	7.3
0.5	--	8.6	--	8.0	--
1.0	6.7	--	8.0	--	8.1
2.0	--	10.9	--	8.7	--
5.0	16.6	--	8.7	--	8.7
			Second Harvest		
0	8.1	--	4.7	--	5.3
0.5	--	6.0	--	5.7	--
1.0	4.5	--	5.8	--	6.3
2.0	--	8.1	--	5.9	--
5.0	12.5	--	6.5	--	6.4
			Third Harvest		
0	9.1	--	5.7	--	5.1
0.5	--	6.9	--	5.9	--
1.0	9.7	--	6.9	--	5.4
2.0	--	8.6	--	6.5	--
5.0	9.9	--	8.3	--	7.1

Table 27. Effects of Mn and $CaCO_3$ on *A. gayanus* forage-Mn concentration from a highly weathered soil from the Colombian Amazon.

Mn applied	$CaCO_3$ applied, meq/100 g				
	0	0.5	1	2	5
ppm	----------Oven-dry forage Mn, ppm----------				
			First Harvest		
0	612	--	416	--	439
0.5	--	493	--	524	--
1.0	525	--	518	--	503
2.0	--	524	--	468	--
5.0	609	--	500	--	503
			Second Harvest		
0	628	--	517	--	452
0.5	--	603	--	567	--
1.0	592	--	580	--	450
2.0	--	561	--	537	--
5.0	600	--	658	--	431
			Third Harvest		
0	506	--	475	--	406
0.5	--	601	--	484	--
1.0	517	--	532	--	425
2.0	--	506	--	481	--
5.0	520	--	567	--	406

Table 28. Effects of Mn and P on *A. gayanus* forage-Mn concentration from a highly weathered soil from the Colombian Amazon.

Mn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	----------Oven-dry forage Mn, ppm----------				
			First Harvest		
0	540	--	416	--	466
0.5	--	468	--	521	--
1.0	599	--	487	--	500
2.0	--	471	--	522	--
5.0	668	--	500	--	443
			Second Harvest		
0	520	--	517	--	560
0.5	--	536	--	634	--
1.0	363	--	594	--	592
2.0	--	505	--	593	--
5.0	408	--	658	--	527
			Third Harvest		
0	362	--	475	--	549
0.5	--	554	--	531	--
1.0	325	--	544	--	542
2.0	--	500	--	487	--
5.0	375	--	567	--	478

Table 29. Effects of $CaCO_3$ and P on *A. gayanus* forage-Mn concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	----------Oven-dry forage Mn, ppm----------				
			First Harvest		
0	679	--	525	--	497
0.5	--	480	--	537	--
1.0	599	--	487	--	500
2.0	--	459	--	506	--
5.0	529	--	392	--	412
			Second Harvest		
0	619	--	592	--	618
0.5	--	530	--	634	--
1.0	363	--	616	--	592
2.0	--	511	--	593	--
5.0	415	--	450	--	468
			Third Harvest		
0	400	--	517	--	566
0.5	--	596	--	512	--
1.0	325	--	561	--	542
2.0	--	459	--	506	--
5.0	350	--	425	--	462

P and lime on Mn concentration in the forage in the third harvest are presented on Fig. 8.

In general, fertilizer P was the primary factor affecting P, Ca, K, Mg, Fe, Zn, and Cu uptake by the grass irrespective of the harvests, due to its effect on forage DM production (Tables 30-37). Increasing levels of P tended to increase ($P < 0.01$) forage uptake of P, K, Ca, Mg, Fe, Zn, Cu, and Mn as indicated in Appendix Tables 6, 7, and 8. Lime did increase Ca, Mg, and Mn uptake in the forage ($P < 0.01$); at the same time it reduced forage uptake of Zn. Lime did not affect the content of Fe in forage probably because only slight changes in soil pH were induced with the rates of lime used (Appendix Tables 6, 7, and 8).

Total forage nutrient uptake values were calculated as the sum of the contents of a particular nutrient for the three harvests. Calculated nutrient uptake values are included at the bottom of the tables presenting each specific nutrient uptake (Tables 30-37). Levels of significance for total forage nutrient uptake are presented in Appendix Table 9. Discussion of total forage nutrient uptake resembles closely the one intended for nutrient uptake by harvests. Fertilizer P increased ($P < 0.01$) total forage uptake of P, K, Ca, Mg, Fe, Zn, Cu, and Mn. Lime increased ($P < 0.01$) total forage uptake of Ca and Mg but depressed ($P < 0.01$) Zn uptake. The positive effect of lime on Mn uptake was likely due to increased Mn absorption by the forage at lime rates of 1 meq $CaCO_3$/100 g of soil or less, and 32.5 ppm P or less. Total forage Mg uptake was reduced ($P < 0.01$) by lime x P interaction, probably due to reduction in DM yields at lime levels greater than 1 meq $CaCO_3$/100 g of soil combined with rates of applied P over 32.5 ppm.

$$Z = 429.8816 + 129.4169 \mathrm{Log}\ P - 31.8053(\mathrm{Log}\ P)^2 - 20.2087L$$

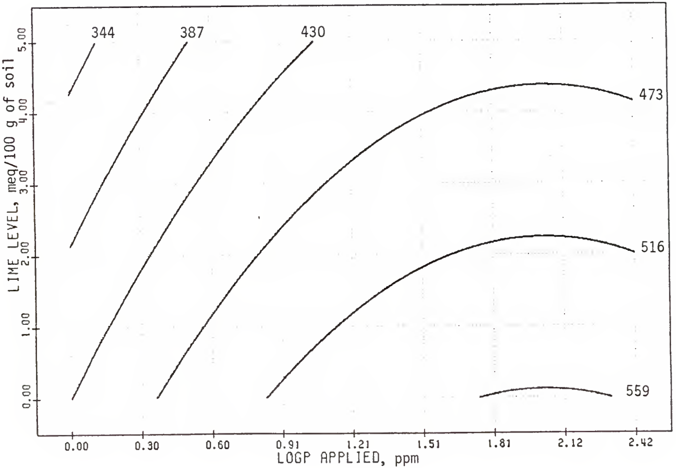

Figure 8. Contours of predicted forage Mn concentration (ppm) of *A. gayanus* in the third harvest as affected by lime and P.

Table 30. Effects of $CaCO_3$ and P on *A. gayanus* forage-P uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Forage P, mg/pot				
			First Harvest		
0	0.03	--	12.2	--	29.3
0.5	--	5.6	--	18.8	--
1.0	0.04	--	12.5	--	33.2
2.0	--	6.0	--	18.4	--
5.0	0.07	--	10.3	--	28.6
			Second Harvest		
0	0.16	--	4.1	--	15.5
0.5	--	3.0	--	9.9	--
1.0	0.22	--	6.0	--	18.6
2.0	--	2.8	--	10.5	--
5.0	0.21	--	6.6	--	16.9
			Third Harvest		
0	1.7	--	4.7	--	12.9
0.5	--	2.3	--	7.8	--
1.0	2.4	--	4.6	--	15.8
2.0	--	3.1	--	8.6	--
5.0	2.1	--	4.9	--	15.2
			Total		
0	1.9	--	21.1	--	57.7
0.5	--	11.0	--	36.6	--
1.0	2.7	--	23.2	--	67.6
2.0	--	11.9	--	37.5	--
5.0	2.5	--	21.8	--	60.7

Table 31. Effects of $CaCO_3$ and P on *A. gayanus* forage-Ca uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Forage Ca, mg/pot				
	First Harvest				
0	0.16	--	17.0	--	17.6
0.5	--	8.9	--	21.4	--
1.0	0.27	--	18.1	--	25.4
2.0	--	13.9	--	27.7	--
5.0	0.74	--	29.9	--	35.5
	Second Harvest				
0	0.31	--	17.9	--	29.9
0.5	--	13.0	--	33.1	--
1.0	0.41	--	31.5	--	38.6
2.0	--	16.8	--	40.0	--
5.0	2.10	--	47.3	--	50.9
	Third Harvest				
0	2.8	--	18.4	--	32.4
0.5	--	12.9	--	30.3	--
1.0	5.7	--	28.4	--	39.8
2.0	--	19.4	--	39.3	--
5.0	16.3	--	44.8	--	58.0
	Total				
0	3.4	--	53.4	--	79.9
0.5	--	34.8	--	84.8	--
1.0	6.8	--	81.3	--	103.8
2.0	--	50.2	--	107.1	--
5.0	14.8	--	122.0	--	144.4

Table 32. Effects of $CaCO_3$ and P on *A. gayanus* forage-K uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Forage K, mg/pot				
			First Harvest		
0	0.68	--	136	--	121
0.5	--	71	--	130	--
1.0	0.73	--	132	--	110
2.0	--	79	--	124	--
5.0	1.33	--	103	--	112
			Second Harvest		
0	1.50	--	71	--	98
0.5	--	60	--	95	--
1.0	3.35	--	86	--	105
2.0	--	57	--	98	--
5.0	3.50	--	100	--	96
			Third Harvest		
0	41	--	75	--	76
0.5	--	47	--	70	--
1.0	47	--	62	--	77
2.0	--	60	--	72	--
5.0	74	--	64	--	72
			Total		
0	46	--	282	--	294
0.5	--	184	--	295	--
1.0	54	--	283	--	292
2.0	--	197	--	294	--
5.0	82	--	267	--	281

Table 33. Effects of $CaCO_3$ and P on *A. gayanus* forage-Mg uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-------------Forage Mg, mg/pot-------------				
			First Harvest		
0	0.17	--	17	--	20
0.5	--	6	--	21	--
1.0	0.11	--	17	--	23
2.0	--	7	--	20	--
5.0	0.15	--	13	--	16
			Second Harvest		
0	0.28	--	14	--	33
0.5	--	8	--	32	--
1.0	0.23	--	24	--	34
2.0	--	7	--	31	--
5.0	0.44	--	18	--	25
			Third Harvest		
0	3.2	--	12	--	24
0.5	--	7	--	20	--
1.0	3.7	--	16	--	26
2.0	--	7	--	22	--
5.0	4.2	--	13	--	23
			Total		
0	3.7	--	43	--	79
0.5	--	21	--	73	--
1.0	4.3	--	57	--	83
2.0	--	22	--	74	--
5.0	4.9	--	43	--	65

Table 34. Effects of Fe and P on *A. gayanus* forage-Fe uptake from a highly weathered soil from the Colombian Amazon.

Fe applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Forage Fe, μg/pot				
			First Harvest		
0	20	--	953	--	1185
2	--	609	--	1079	--
5	21	--	944	--	1144
10	--	363	--	959	--
20	21	--	847	--	1104
			Second Harvest		
0	41	--	690	--	1324
2	--	598	--	1132	--
5	18	--	978	--	1142
10	--	778	--	1075	--
20	46	--	859	--	988
			Third Harvest		
0	671	--	956	--	1889
2	--	946	--	1918	--
5	--+	--	1328	--	842
10	--	615	--	1319	--
20	1040	--	1491	--	2126
			Total		
0	740	--	2600	--	4399
2	--	2074	--	4230	--
5	--+	--	3255	--	3128
10	--	1865	--	3258	--
20	1108	--	3197	--	4220

+Missing values.

Table 35. Effects of Zn and P on *A. gayanus* forage-Zn uptake from a highly weathered soil from the Colombian Amazon.

Zn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Forage Zn, µg/pot				
			First Harvest		
0	3.1	--	159	--	204
0.5	--	139	--	198	--
1.0	21	--	237	--	221
2.0	--	98	--	258	--
5.0	6.6	--	304	--	270
			Second Harvest		
0	14	--	268	--	364
0.5	--	151	--	348	--
1.0	9	--	334	--	408
2.0	--	138	--	469	--
5.0	14	--	569	--	532
			Third Harvest		
0	150	--	159	--	269
0.5	--	122	--	279	--
1.0	86	--	227	--	349
2.0	--	120	--	286	--
5.0	175	--	302	--	462
			Total		
0	167	--	585	--	837
0.5	--	413	--	826	--
1.0	116	--	799	--	978
2.0	--	356	--	1012	--
5.0	196	--	1176	--	1265

Table 36. Effects of Cu and P on *A. gayanus* forage-Cu uptake from a highly weathered soil from the Colombian Amazon.

Cu applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Forage Cu, μg/pot				
			First Harvest		
0	0.4	--	46	--	51
0.5	--	35	--	55	--
1.0	2.8	--	52	--	60
2.0	--	23	--	60	--
5.0	0.9	--	55	--	60
			Second Harvest		
0	1.6	--	38	--	60
0.5	--	28	--	53	--
1.0	9	--	49	--	70
2.0	--	28	--	61	--
5.0	3.1	--	54	--	63
			Third Harvest		
0	45	--	38	--	52
0.5	--	34	--	57	--
1.0	26	--	49	--	57
2.0	--	34	--	55	--
5.0	35	--	58	--	73
			Total		
0	49	--	123	--	163
0.5	--	97	--	166	--
1.0	38	--	152	--	187
2.0	--	85	--	178	--
5.0	39	--	167	--	196

Table 37. Effects of $CaCO_3$ and P on *A. gayanus* forage Mn uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Forage Mn, µg/pot				
			First Harvest		
0	29	--	3563	--	3566
0.5	--	1406	--	3807	--
1.0	32	--	3216	--	3796
2.0	--	1516	--	3395	--
5.0	46	--	2101	--	2750
			Second Harvest		
0	107	--	3645	--	6865
0.5	--	2240	--	6651	--
1.0	62	--	5378	--	6647
2.0	--	2207	--	5867	--
5.0	127	--	3978	--	4635
			Third Harvest		
0	1271	--	3515	--	5876
0.5	--	2196	--	4565	--
1.0	877	--	3998	--	5767
2.0	--	2175	--	4608	--
5.0	1357	--	3061	--	4702
			Total		
0	1409	--	10723	--	16308
0.5	--	5843	--	15024	--
1.0	971	--	12593	--	16209
2.0	--	5375	--	13870	--
5.0	1531	--	9140	--	12088

Root Nutrient Concentrations and Uptake

Increasing levels of P tended to increase P concentration in the root system regardless of lime or micronutrient rates used. Concentrations of P in the roots (Table 38) were very similar to those reported in the forage for the second and third harvests (Table 18).

Lime had a small positive effect ($P < 0.01$) on root P concentration (Table 38 and Appendix Table 10), probably as a result of the reduction in the exchangeable Al levels in the soil, and consequently, improvement in root P absorption. Lime also increased ($P < 0.01$) Ca root concentration and depressed ($P < 0.01$) Zn and Mn levels within the roots (Tables 39, 42, 45, and Appendix Table 10). No significant effect of lime on root concentration of K, Mg, and Cu was detected (Tables 40, 41, and Appendix Table 10).

Fertilizer P applications reduced ($P < 0.01$) concentration of K, Ca, Mg, Zn, Cu, and Mn in the root system (Tables 40-45 and Appendix Table 10), probably as an indirect effect due to increased root DM production. Effects of P and lime on root Ca concentration are depicted in Fig. 9. Their effects on Mn concentration are presented in Fig. 10. As in the case of forage, absorption of P, K, Ca, Mg, Zn, Cu, and Mn was directly related to level of P applied to the soil, and to the level of the particular nutrient used (Tables 46-53). Phosphorus increased ($P < 0.01$) the root uptake of every nutrient considered (Appendix Table 11) due to increased DM production. Lime had a positive effect ($P < 0.01$) on root Ca uptake and a negative effect ($P < 0.01$) on root Zn uptake (Table 47 and Appendix Table 11).

Table 38. Effects of $CaCO_3$ and P on *A. gayanus* root-P concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Oven-dry root P, %------------				
0	0.08	--	0.07	--	0.15
0.5	--	0.06	--	0.10	--
1.0	0.10	--	0.07	--	0.17
2.0	--	0.07	--	0.10	--
5.0	0.09	--	0.07	--	0.17

Table 39. Effects of $CaCO_3$ and P on *A. gayanus* root-Ca concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Oven-dry root Ca, %------------				
0	0.11	--	0.13	--	0.11
0.5	--	0.14	--	0.13	--
1.0	0.17	--	0.18	--	0.15
2.0	--	0.16	--	0.16	--
5.0	0.40	--	0.28	--	0.23

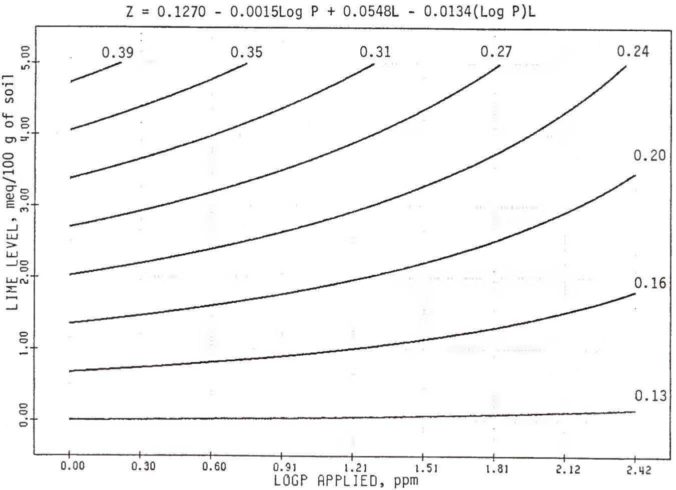

Figure 9. Contours of predicted root Ca concentration (%) of *A. gayanus* as affected by lime and P.

Table 40. Effects of $CaCO_3$ and P on *A. gayanus* root-K concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Oven-dry root K, %------------				
0	1.18	--	0.48	--	0.39
0.5	--	0.53	--	0.36	--
1.0	1.28	--	0.43	--	0.35
2.0	--	0.59	--	0.36	--
5.0	1.11	--	0.53	--	0.41

Table 41. Effects of $CaCO_3$ and P on *A. gayanus* root-Mg concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	------------Oven-dry root Mg, %------------				
0	0.13	--	0.10	--	0.09
0.5	--	0.10	--	0.09	--
1.0	0.19	--	0.10	--	0.10
2.0	--	0.09	--	0.09	--
5.0	0.12	--	0.09	--	0.10

Table 42. Effects of Zn and $CaCO_3$ on *A. gayanus* root-Zn concentration from a highly weathered soil from the Colombian Amazon.

Zn applied	$CaCO_3$ applied, meq/100 g				
	0	0.5	1	2	5
ppm	-----------Oven-dry root Zn, ppm-----------				
0	127	--	67	--	79
0.5	--	77	--	60	--
1.0	90	--	104	--	48
2.0	--	105	--	80	--
5.0	200	--	194	--	157

Table 43. Effects of Zn and P on *A. gayanus* root-Zn concentration from a highly weathered soil from the Colombian Amazon.

Zn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	-----------Oven-dry root Zn, ppm-----------				
0	124	--	67	--	82
0.5	--	69	--	67	--
1.0	142	--	87	--	100
2.0	--	81	--	104	--
5.0	175	--	194	--	170

Table 44. Effects of Cu and P on *A. gayanus* root-Cu concentration from a highly weathered soil from the Colombian Amazon.

Cu applied	P applied, ppm				
	0	32.5	65	130	260
ppm	-----------Oven-dry root Cu, ppm-----------				
0	17.3	--	12.8	--	12.3
0.5	--	15.0	--	12.3	--
1.0	17.6	--	14.7	--	14.6
2.0	--	17.1	--	14.5	--
5.0	10.9	--	17.1	--	20.3

Table 45. Effects of $CaCO_3$ and P on *A. gayanus* root-Mn concentration from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-------------Oven-dry Mn, ppm-------------				
0	288	--	331	--	258
0.5	--	310	--	272	--
1.0	415	--	341	--	277
2.0	--	236	--	212	--
5.0	302	--	206	--	209

$$Z = 349.3741 + 4.8869 \text{Log } P - 15.8309(\text{Log } P)^2 - 13.8934L$$

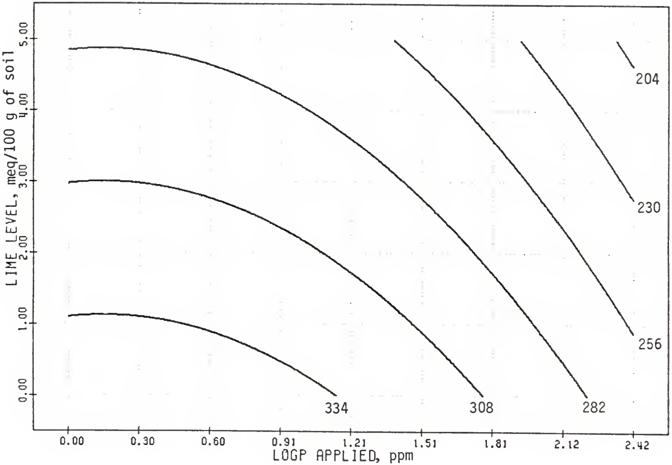

Figure 10. Contours of predicted root Mn concentration (ppm) of *A. gayanus* as affected by lime and P.

Table 46. Effects of $CaCO_3$ and P on *A. gayanus* root-P uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Root P, mg/pot				
0	1.5	--	7.4	--	26.1
0.5	--	4.6	--	16.0	--
1.0	2.9	--	9.2	--	27.5
2.0	--	6.3	--	17.4	--
5.0	2.3	--	8.3	--	23.9

Table 47. Effects of $CaCO_3$ and P on *A. gayanus* root-Ca uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ uptake	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Root Ca, mg/pot				
0	2.8	--	13.8	--	19.2
0.5	--	11.0	--	21.8	--
1.0	5.2	--	23.4	--	25.7
2.0	--	13.4	--	26.6	--
5.0	9.6	--	31.0	--	33.0

Table 48. Effects of $CaCO_3$ and P on *A. gayanus* root-K uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
ppm	--------------Root K, mg/pot---------------				
0	30	--	45	--	68
0.5	--	41	--	57	--
1.0	38	--	56	--	59
2.0	--	47	--	61	--
5.0	30	--	59	--	56

Table 49. Effects of $CaCO_3$ and P on *A. gayanus* root-Mg uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	--------------Root Mg, mg/pot--------------				
0	2.3	--	11	--	15
0.5	--	7	--	15	--
1.0	5.7	--	13	--	17
2.0	--	7	--	15	--
5.0	3.2	--	10	--	14

Table 50. Effects of Zn and P on *A. gayanus* root-Zn uptake from a highly weathered soil from the Colombian Amazon.

Zn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Root Zn, µg/pot				
0	313	--	758	--	1298
0.5	--	454	--	1100	--
1.0	426	--	1136	--	1640
2.0	--	620	--	1680	--
5.0	372	--	2547	--	2642

Table 51. Effects of Cu and P on *A. gayanus* root-Cu uptake from a highly weathered soil from the Colombian Amazon.

Cu applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Root Cu, µg/pot				
0	36	--	145	--	191
0.5	--	116	--	200	--
1.0	53	--	188	--	241
2.0	--	130	--	239	--
5.0	43	--	226	--	312

Table 52. Effects of Mn and P on *A. gayanus* root-Mn uptake from a highly weathered soil from the Colombian Amazon.

Mn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	--------------Root Mn, μg/pot--------------				
0	673	--	3879	--	3501
0.5	--	2283	--	3905	--
1.0	1245	--	4094	--	4561
2.0	--	1937	--	3991	--
5.0	605	--	4515	--	3816

Table 53. Effects of $CaCO_3$ and P on *A. gayanus* root-Mn uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	--------------Root Mn, μg/pot--------------				
0	506	--	3489	--	4420
0.5	--	2293	--	4407	--
1.0	1245	--	4528	--	4561
2.0	--	1927	--	3489	--
5.0	723	--	2302	--	2897

Biomass Yield and Nutrient Uptake

Biomass yield or total plant yield was calculated as the summation of the dry matter produced in the three forage harvests plus the dry matter produced by the root mass immediately after the third harvest. Biomass yield was directly dependent on fertilizer P application (Table 54) as previously reported for the forage and the root system of *A. gayanus*. The depressing effect ($P < 0.01$) of the lime x P interaction (Appendix Table 2) was a prolongation of the same depressing effect reported before for root growth (Appendix Table 2). This depressing effect of the combination of lime and P at high rates of application on biomass DM yields may be regarded as an example of the detrimental effects of overliming (Kamprath, 1971) applicable in this grass to reduction in P uptake (Table 49). No clear-cut effect on biomass DM production due to a micronutrient imbalance was detected.

Biomass P, Ca, K, Mg, Zn, and Cu uptake were directly dependent ($P < 0.01$) on the level of P applied (Tables 55-62 and Appendix Table 12). Lime had a negative effect ($P < 0.01$) on Zn and Cu biomass uptake (Appendix Table 12) but increased ($P < 0.01$) Mn biomass uptake (Table 62 and Appendix Table 12). The interaction of lime x P reduced ($P < 0.01$) plant Mn uptake as an effect of depressed DM production (Appendix Table 12).

Recovery of P and Ca Applied

Apparent recovery of P and Ca are calculated as the difference in nutrient uptake by the whole plant (forage + roots) at a given

Table 54. Effects of $CaCO_3$ and P on *A. gayanus* biomass dry matter from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	----------Oven-dry biomass, g/pot----------				
0	1.1	--	30.5	--	45.6
0.5	--	18.2	--	42.5	--
1.0	2.1	--	34.6	--	45.8
2.0	--	20.1	--	42.6	--
5.0	3.0	--	32.5	--	40.4

Table 55. Effects of $CaCO_3$ and P on *A. gayanus* biomass-P uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	-------------Biomass P, mg/pot-------------				
0	3.5	--	30.5	--	83.8
0.5	--	15.7	--	52.6	--
1.0	5.8	--	31.6	--	95.1
2.0	--	18.3	--	54.9	--
5.0	5.8	--	30.1	--	84.7

Table 56. Effects of $CaCO_3$ and P on *A. gayanus* biomass-Ca uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Biomass Ca, mg/pot				
0	9.6	--	67.2	--	99.1
0.5	--	45.8	--	106.7	--
1.0	12.0	--	100.8	--	129.5
2.0	--	63.5	--	133.7	--
5.0	28.1	--	153.0	--	177.5

Table 57. Effects of $CaCO_3$ and P on *A. gayanus* biomass-K uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Biomass K, mg/pot				
0	113	--	327	--	362
0.5	--	227	--	352	--
1.0	92	--	337	--	351
2.0	--	245	--	355	--
5.0	97	--	326	--	337

Table 58. Effects of $CaCO_3$ and P on *A. gayanus* biomass-Mg uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Biomass Mg, mg/pot				
0	6	--	54	--	94
0.5	--	29	--	87	--
1.0	10	--	70	--	100
2.0	--	28	--	89	--
5.0	8	--	52	--	79

Table 59. Effects of Zn and P on *A. gayanus* biomass-Zn uptake from a highly weathered soil from the Colombian Amazon.

Zn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Biomass Zn, μg/pot				
0	484	--	1344	--	2136
0.5	--	958	--	1927	--
1.0	532	--	1935	--	2617
2.0	--	976	--	2693	--
5.0	568	--	3723	--	3907

Table 60. Effects of Cu and P on biomass-Cu uptake by *A. gayanus* from a highly weathered soil from the Colombian Amazon.

Cu applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Biomass Cu, μg/pot				
0	65	--	296	--	463
0.5	--	205	--	396	--
1.0	91	--	351	--	429
2.0	--	224	--	387	--
5.0	105	--	298	--	399

Table 61. Effects of Mn and P on *A. gayanus* biomass-Mn uptake from a highly weathered soil from the Colombian Amazon.

Mn applied	P applied, ppm				
	0	32.5	65	130	260
ppm	Biomass Mn, μg/pot				
0	2247	--	13778	--	18626
0.5	--	8492	--	19047	--
1.0	2216	--	16243	--	20770
2.0	--	6724	--	17745	--
5.0	1941	--	17148	--	17088

Table 62. Effects of $CaCO_3$ and P on *A. gayanus* biomass-Mn uptake from a highly weathered soil from the Colombian Amazon.

$CaCO_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	Biomass Mn, μg/pot				
0	1915	--	14212	--	20729
0.5	--	8136	--	19432	--
1.0	2216	--	17122	--	20770
2.0	--	7080	--	17360	--
5.0	2260	--	11442	--	14985

level of application of lime or P minus the uptake at the 0 level of applied P or $CaCO_3$.

Apparent recovery of P ranged from 23% at the 65 ppm P level and 0 meq $CaCO_3$/100 g of soil treatment combinations to 7% at the 260 ppm P and both 0 and 5 meq $CaCO_3$/100 g of soil (Table 63). The apparent P recovered values were considered relatively high, indicative of acute deficiency of available P in the soil. Both lime and P at increasing rates tended to reduce apparent P recovery of *A. gayanus*.

Apparent recovery of Ca was extremely low (Table 64). In ranged from 0.6% at the 1 meq $CaCO_3$/100 g of soil and 0 ppm P treatment combinations to 8.2% at the same level of $CaCO_3$ combined with 65 ppm P. Application of lime at a rate greater than 0 meq $CaCO_3$/100 g of soil combined with a rate of fertilizer P greater than or equal to 65 ppm tended to reduce recovery of Ca. The low recovery of Ca obtained coupled with the little effect of lime on DM production may have emphasized that the real requirement of Ca for adequate growth of *A. gayanus* was minimal.

Table 63. Effects of CaCO$_3$ and P on apparent-P recovery by *A. gayanus* in a highly weathered soil from the Colombian Amazon.

CaCO$_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	--------------Recovered P, %--------------				
0	--		23		7
0.5					
1.0	--		22		8
2.0					
5.0	--		21		7

Table 64. Effects of CaCO$_3$ and P on apparent-Ca recovery by *A. gayanus* in a highly weathered soil from the Colombian Amazon.

CaCO$_3$ applied	P applied, ppm				
	0	32.5	65	130	260
meq/100 g	--------------Recovered Ca, %-------------				
0	--		--		--
0.5					
1.0	0.6		8.2		7.4
2.0					
5.0	0.9		4.2		3.9

SUMMARY AND CONCLUSIONS

A greenhouse experiment was conducted to study the effect of five levels each of lime, P, and micronutrients on dry matter production, nutrient concentration, and nutrient uptake in *Andropogon gayanus* Kunth, and on selected soil characteristics in a highly weathered soil from the Colombian Amazon.

The experimental treatments were arranged in a modified central composite response surface design in three factors ($CaCO_3$, P, and micronutrients) each at five levels. Calcium carbonate was applied at rates of 0, 0.5, 1, 2, and 5 meq/100 g of soil. Phosphorus was applied as KH_2PO_4 and $NH_4H_2PO_4$ at rates of 0, 32.5, 65, 130, and 260 ppm, equivalent to 0, 1/32, 1/16, 1/8, and 1/4 the P adsorption maximum as calculated by the Langmuir equation. Iron was applied at rates of 0, 2, 5, 10, and 20 ppm Fe. Zinc, Cu, B, and Mn were each applied at rates of 0, 0.5, 1, 2, or 5 ppm. Sulfates were used as the sources of Fe, Zn, Cu, and Mn. Boric acid was used as the source of B. All the micronutrients included in each level of application were applied concurrently.

Nitrogen, K, and Mg were applied as a basal solution containing 100 ppm N as NH_4NO_3, 50 ppm K as KCl, and 25 ppm Mg as $MgSO_4 \cdot 7H_2O$. Application of N and K in solution were repeated after each harvest. In addition, an N application of 50 ppm in solution as NH_4NO_3 was made at the middle of the growth period prior to each harvest.

Lime was allowed to react with the soils for 30 days before planting. Plant populations were thinned to 3 plants/pot 5 days after germination, and then the P and micronutrient treatment solutions were applied. Three harvests were made during the experiment. The first harvest was made 57 days after planting, with subsequent harvests after 59 and 56 days of regrowth, respectively. Top growth samples from each harvest were analyzed for P, K, Ca, Mg, Fe, Zn, Cu, and Mn. Root samples collected after the third harvest were analyzed for the same elements minus Fe. Soil samples taken at the end of the experiment were analyzed for pH, exchangeable Al and Ca, effective cation exchange capacity (ECEC), and double-acid extractable P, K, Ca, and Mg.

The following conclusions can be drawn from the experiment:

1. Lime increased pH, exchangeable Ca, extractable Ca and Mg, and decreased Al saturation and extractable P in the soil.
2. The original level of P in the soil--3 ppm--severely limited growth of *A. gayanus*. Without P application, symptoms of P deficiency developed early and growth was impaired.
3. The largest increase in forage dry matter occurred at the first increment of P (32.5 ppm) although response continued with smaller increases through the rate of 260 ppm P applied.
4. Neither lime nor micronutrients significantly increased forage or root dry matter production.
5. Application of P increased P and Mg concentration in the forage and root system of *A. gayanus*, but decreased all the other nutrient concentrations due to increased dry matter yields. Phosphorus increased uptake of all the nutrients studied in the forage and roots.

6. Lime increased Ca concentration in the forage and in the root mass, but decreased Zn and Mn concentrations. No effect on Fe concentration was found.
7. Manganese concentrations in the forage were higher than those in the root system. Support is given to the idea that probably high levels of Mn in the soil will affect forage production rather than root growth for some plant species in tropical soils.
8. High apparent recovery of applied P was observed in *A. gayanus* planted on the soil studied.
9. Apparent recovery of Ca was low compared to the amount applied, although plant Ca content was markedly increased in the whole plant as a consequence of P applications.
10. Growth of *A. gayanus* did not pass the peak of maximum forage dry matter production even at the rate of 260 ppm P applied. In the range of applied P from 0 to 260 ppm, the response in forage dry matter tended to follow an apparent asymptotic relationship at the highest P applications.

APPENDIX

Appendix Table 1. Levels of significance for sources of variation affecting selected chemical characteristics of a highly weathered soil from the Colombian Amazon after the removal of three harvests of *A. gayanus*.

Source of variation	pH		Exch. Al	Exch. Ca	ECEC	Al Sat.	Double-acid extractable			
	H_2O	KCl					P	K	Ca	Mg
L	**(+)	**(+)	**(-)	**(+)	**(+)	**(-)		**(-)	**(+)	**(+)
L x L	**(+)	*(+)	**(+)			*(-)		**(+)	**(-)	
P^+	**(-)	**(-)	**(+)	**(-)	**(+)	**(+)	**(-)	**(-)		
P x P	**(+)	**(-)					**(+)	**(+)		
Mic										
Mic x Mic										
L x P	**(+)	**(+)	**(-)	**(+)	**(-)	**(-)				
L x Mic										
P x Mic										

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$). blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 2. Levels of significance for sources of variation affecting DM yields of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage DM yield				Root yield	Biomass yield
	1st harvest	2nd harvest	3rd harvest	Total		
L					**(+)	
L x L					**(-)	
P^+	**(+)	**(+)	**(+)	**(+)	**(+)	**(+)
P x P		**(+)	**(+)	**(+)		**(+)
Mic						
Mic x Mic						
L x P					**(-)	**(-)
L x Mix						
P x Mic						

$^+$ = Log P transformation.

* = $(P < 0.05)$.

** = $(P < 0.01)$. blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 3. Levels of significance for sources of variation affecting forage nutrient concentrations in the first harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient concentrations							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L			**(+)	**(+)	**(-)	**(-)	**(-)	**(-)
L x L			**(-)	*(-)	*(-)		**(+)	
P^{+}	**(-)	**(+)	**(-)	**(-)	**(-)	**(-)	**(-)	**(-)
P x P	**(+)	**(-)	**(+)	**(+)	**(+)			
Mic				*(+)	**(+)	**(+)	**(+)	**(+)
Mic x Mic					**(-)	**(+)		
L x P			**(-)	**(-)	**(+)	**(+)	**(+)	
L x Mic				**(-)	*(-)	**(-)	**(-)	
P x Mic						**(-)	**(-)	**(-)

$^{+}$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$). blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 4. Levels of significance for sources of variation affecting forage nutrient concentrations in the second harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient concentrations							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L				**(+)		**(-)		**(-)
L x L			**(+)	*(-)				
P^+	**(-)	**(-)	**(-)	**(-)	**(-)	**(-)	**(+)	**(+)
P x P	**(+)	*(-)		**(+)				
Mic		*(+)				*(-)		*(-)
Mic x Mic						**(+)		
L x P			**(-)			**(+)		
L x Mic	**(+)							
P x Mic								

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 5. Levels of significance for sources of variation affecting forage nutrient concentrations in the third harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient concentrations						
	P	K	Ca	Mg	Zn	Cu	Mn
L	**(+)		**(+)	**(-)	**(-)		**(-)
L x L			*(-)				
P^+	**(-)	**(-)	**(+)	**(+)	**(-)	**(-)	**(+)
P x P	**(+)		**(-)		*(+)		**(-)
Mic				**(-)	**(+)	**(+)	
Mic x Mic						**(-)	
L x P							
L x Mic							
P x Mic							

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 6. Levels of significance for sources of variation affecting nutrient uptake in the first harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient uptake							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L			**(+)	**(+)		**(-)	**(+)	**(-)
L x L								
P^+	**(-)	**(+)	**(+)	**(+)	**(+)	**(+)	**(+)	**(-)
P x P	**(+)	**(-)		*(+)				
Mic			*(-)		**(-)			
Mic x Mic					**(+)		*(+)	**(+)
L x P				*(-)		**(-)	*(-)	
L x Mic								
P x Mic						**(+)		**(-)

$^+$ = Log P gransformation.

* = (P < 0.05).

** = (P < 0.01).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 7. Levels of significance for sources of variation affecting nutrient uptake in the second harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient uptake							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L			**(+)	**(+)		**(-)		**(+)
L x L				**(-)				
P^+	**(-)	**(+)	**(+)	**(-)	**(-)	**(+)	**(+)	**(+)
P x P	**(+)			**(+)				
Mic			*(-)			**(+)		
Mic x Mic								
L x P				**		*(-)		**(-)
L x Mic								
P x Mic								

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 8. Levels of significance for sources of variation affecting nutrient uptake in the third harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Forage nutrient uptake							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L			**(+)			**(-)		*(-)
L x L								
P^+	**(-)	**(-)	**(+)	**(-)	**(+)	*(-)	**(-)	**(-)
P x P	**(+)	**(+)	**(+)	**(+)		**(+)	*(+)	**(+)
Mic					*(-)	**(+)	**(+)	
Mic x Mic					**(+)	**(+)	*(+)	
L x P								
L x Mic								
P x Mic								

$^+$ = Log P transformation.

* = (P < 0.05).

** = (P < 0.01).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 9. Levels of significance for sources of variation affecting total forage nutrient uptake by *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Total forage nutrient uptake							
	P	K	Ca	Mg	Fe	Zn	Cu	Mn
L			**(+)	**(+)		**(-)		**(+)
L x L				*(-)				
P^+	**(-)	**(+)	**(+)	**(-)	**(+)	**(-)	**(+)	*(+)
P x P	**(+)	*(-)		**(+)		**(+)		**(+)
Mic				*(-)	*(+)	**(+)	**(+)	
Mic x Mic								
L x P				*(-)				*(-)
L x Mic								
P x Mic								

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 10. Levels of significance for sources of variation affecting root nutrient concentrations following the third harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Root nutrient concentrations						
	P	K	Ca	Mg	Zn	Cu	Mn
L	**(+)		**(+)		**(-)		**(-)
L x L							
P^+	**(-)	**(-)	**(-)	**(-)	**(-)	**(-)	**(+)
P x P	**(+)	**(+)		**(+)	**(+)		**(-)
Mic					**(+)	**(+)	
Mic x Mic					**(+)		
L x P							
L x Mic							
P x Mic						*(+)	

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 11. Levels of significance for sources of variation affecting nutrient uptake by *A. gayanus* roots on a highly weathered soil from the Colombian Amazon.

Source of variation	Root nutrient uptake						
	P	K	Ca	Mg	Zn	Cu	Mn
L			**(+)		**(-)		**(+)
L x L							
P[+]	**(-)	**(+)	**(+)	**(+)	**(-)	**(+)	**(+)
P x P	**(+)				*(+)		
Mic					**(+)	**(+)	
Mic x Mic					*(+)		
L x P							*(-)
L x Mic					**(-)		
P x Mic					*(+)	*(+)	

[+] = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 12. Levels of significance for sources of variation affecting biomass nutrient uptake by *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Source of variation	Biomass nutrient uptake						
	P	K	Ca	Mg	Zn	Cu	Mn
L			**(+)	**(+)	*(-)	*(-)	**(+)
L x L				**(-)			
P^+	(-)	**(-)	**(+)	**(-)	*(-)	**(+)	**(+)
P x P	(+)			**(+)	**(+)		
Mic					**(+)	**(+)	
Mic x Mic					**(+)		
L x P		*(-)					**(-)
L x Mic							
P x Mic							

$^+$ = Log P transformation.

* = ($P < 0.05$).

** = ($P < 0.01$).

blank = NS.

Response to source of variation is positive (+) or negative (-).

Appendix Table 13. Treatment combinations and selected chemical characteristics of a highly weathered soil from the Colombian Amazon following the removal of three harvests of *A. gayanus*.

Treatment				pH						Double-acid ext. nutrients			
L	P	Mic	Rep	H_2O	KCl	Exch. Al	Exch. Ca	ECEC	Al Sat.	P	K	Ca	Mg
Coded levels			No.			------------meq/100 g------			%	----------ppm----------			
-2	-2	-2	6	4.45	3.78	3.3	1.1	6.1	55.2	3.5	99	182	32
-2	-2	2	6	4.42	3.77	3.3	1.1	6.0	54.3	3.8	108	164	47
-2	0	0	3	4.16	3.67	5.0	1.1	7.7	64.3	6.9	16	175	41
-2	2	-2	6	4.24	3.60	5.1	1.1	7.7	65.6	25.7	16	151	47
-2	2	2	6	4.24	3.61	4.8	1.2	7.6	63.2	26.8	20	177	33
-1	-1	-1	4	4.34	3.76	3.6	1.5	6.5	54.9	5.4	35	279	47
-1	-1	1	4	4.38	3.78	3.4	1.6	6.3	53.1	5.5	54	277	25
-1	1	-1	4	4.21	3.68	4.7	1.6	7.5	62.8	13.5	19	269	22
-1	1	1	4	4.18	3.69	4.7	1.5	7.5	62.6	12.8	20	267	38
0	-2	0	3	4.56	3.85	2.8	1.9	6.1	46.4	3.6	91	262	47
0	0	-2	3	4.25	3.72	4.3	1.9	7.4	57.5	8.7	15	275	37
0	0	0	12	4.21	3.68	4.4	2.0	7.6	57.7	7.8	15	283	35
0	0	2	3	4.22	3.71	4.3	2.0	7.7	56.0	8.6	17	277	36
0	2	0	3	4.42	3.65	4.5	2.0	7.7	58.4	24.1	18	261	25
1	-1	-1	4	4.52	3.85	2.6	2.7	6.6	39.6	4.9	39	474	55
1	-1	1	4	4.42	3.84	2.7	2.7	6.7	39.5	5.3	41	477	55
1	1	-1	4	4.31	3.76	3.4	2.7	7.2	47.9	13.4	23	445	48
1	1	1	4	4.30	3.75	3.6	2.8	7.4	48.2	13.4	21	463	31
2	-2	-2	6	4.60	4.01	1.2	5.0	7.2	16.5	3.2	97	759	53
2	-2	2	6	4.63	4.04	1.2	4.9	7.1	16.4	4.0	97	692	38
2	0	0	3	4.61	3.97	1.4	5.2	7.6	17.9	6.6	17	748	40
2	2	-2	6	4.75	3.95	1.6	5.5	7.8	20.3	23.6	20	693	40
2	2	2	6	4.68	3.93	1.5	5.3	7.7	20.0	23.2	20	770	53

Appendix Table 14. Treatment combinations, forage yields, and nutrient concentrations of the first harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Treatment												
L	P	Mic	Rep	Yield	P	K	Ca	Mg	Fe	Zn	Cu	Mn
Coded levels			No.	g/pot	---------%---------				-------ppm------			
-2	-2	-2	6	0.05	0.08	1.51	0.35	0.21	361	68	6.8	628
-2	-2	2	6	0.04	0.07	1.58	0.43	0.25	493	164	23.9	731
-2	0	0	3	6.77	0.18	2.04	0.25	0.25	127	40	8.1	525
-2	2	-2	6	7.32	0.42	1.69	0.26	0.30	148	32	8.0	508
-2	2	2	6	6.97	0.40	1.72	0.23	0.28	141	46	9.0	487
-1	-1	-1	4	4.50	0.17	2.36	0.30	0.23	136	37	8.2	469
-1	-1	1	4	1.42	0.25	2.52	0.28	0.21	196	53	11.3	494
-1	1	-1	4	7.42	0.26	1.82	0.28	0.31	155	29	7.8	519
-1	1	1	4	6.80	0.27	1.89	0.32	0.28	150	38	8.6	556
0	-2	0	3	0.05	0.07	1.36	0.50	0.20	399	53	6.7	599
0	0	-2	3	5.97	0.22	2.07	0.29	0.25	161	27	7.7	417
0	0	0	12	6.80	0.20	2.02	0.33	0.25	146	37	8.3	502
0	0	2	3	6.30	0.15	1.98	0.33	0.23	137	48	8.7	500
0	2	0	3	7.47	0.45	1.50	0.34	0.31	159	30	8.1	500
1	-1	-1	4	3.62	0.20	2.52	0.41	0.23	178	31	9.0	468
1	-1	1	4	2.87	0.19	2.53	0.43	0.19	162	44	10.5	449
1	1	-1	4	6.40	0.28	1.81	0.43	0.31	160	28	8.2	525
1	1	1	4	7.00	0.27	1.92	0.40	0.29	128	36	8.9	487
2	-2	-2	6	0.08	0.07	1.46	0.85	0.18	285	36	7.3	453
2	-2	2	6	0.09	0.09	1.54	0.81	0.16	253	82	9.4	606
2	0	0	3	5.23	0.20	2.02	0.55	0.23	172	25	6.9	392
2	2	-2	6	6.50	0.43	1.67	0.56	0.27	205	26	6.6	425
2	2	2	6	6.83	0.43	1.73	0.51	0.22	183	33	8.4	400

Appendix Table 15. Treatment combinations, forage yields, and nutrient concentrations of the second harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Treatment L	P	Mic	Rep	Yield	P	K	Ca	Mg	Fe	Zn	Cu	Mn
Coded levels			No.	g/pot	---------%---------				-------ppm------			
-2	-2	-2	6	0.12	0.10	1.66	0.40	0.24	261	168	9.7	619
-2	-2	2	6	0.01	0.08	1.89	--	--	481	--	--	--
-2	0	0	3	6.20	0.06	1.24	0.28	0.22	220	43	5.9	592
-2	2	-2	6	11.98	0.14	0.85	0.27	0.31	114	39	5.6	637
-2	2	2	6	10.16	0.14	0.96	0.27	0.30	95	62	6.6	600
-1	-1	-1	4	5.78	0.07	1.28	0.31	0.21	125	33	5.7	550
-1	-1	1	4	2.57	0.08	1.77	0.31	0.17	204	40	9.1	510
-1	1	-1	4	10.17	0.10	0.91	0.31	0.33	132	40	4.9	656
-1	1	1	4	10.87	0.09	0.91	0.32	0.29	117	48	5.9	612
0	-2	0	3	0.11	0.13	1.97	0.24	0.14	106	51	4.5	363
0	0	-2	3	8.13	0.07	1.07	0.32	0.26	86	33	4.7	517
0	0	0	12	8.92	0.07	0.97	0.37	0.28	110	43	6.0	631
0	0	2	3	8.30	0.06	1.02	0.37	0.27	109	70	6.5	658
0	2	0	3	11.03	0.17	0.98	0.35	0.30	102	37	6.3	592
1	-1	-1	4	3.67	0.08	1.46	0.41	0.20	123	19	6.6	522
1	-1	1	4	4.37	0.07	1.48	0.39	0.16	247	38	7.4	500
1	1	-1	4	10.07	0.11	1.01	0.43	0.31	97	29	5.6	612
1	1	1	4	9.85	0.10	0.97	0.38	0.33	86	44	6.0	575
2	-2	-2	6	0.11	0.12	1.38	--	0.17	174	54	6.6	422
2	-2	2	6	0.25	0.11	1.62	0.85	0.15	136	103	12.5	408
2	0	0	3	8.87	0.07	1.14	0.54	0.20	112	25	5.1	450
2	2	-2	6	10.20	0.16	0.96	0.52	0.27	126	24	5.1	483
2	2	2	6	9.60	0.18	1.02	0.50	0.24	111	43	6.2	454

Appendix Table 16. Treatment combinations, forage yields, and nutrient concentrations of the third harvest of *A. gayanus* on a highly weathered soil from the Colombian Amazon.

Treatment L	P	Mic	Rep	Yield	P	K	Ca	Mg	Fe	Zn	Cu	Mn
Coded levels			No.	g/pot	---------%---------				-------ppm------			
-2	-2	-2	6	1.09	0.07	1.62	0.18	0.19	279	48	10.3	400
-2	-2	2	6	0.00	--	--	--	--	--	--	--	--
-2	0	0	3	6.73	0.07	1.12	0.27	0.17	221	19	6.6	517
-2	2	-2	6	10.08	0.12	0.70	0.32	0.25	156	28	5.1	612
-2	2	2	6	10.48	0.13	0.77	0.31	0.23	211	50	7.1	521
-1	-1	-1	4	3.77	0.06	1.12	0.36	0.20	319	28	6.1	683
-1	-1	1	4	3.67	0.07	1.46	0.36	0.15	129	32	9.8	506
-1	1	-1	4	9.67	0.09	0.75	0.33	0.24	190	29	5.7	519
-1	1	1	4	8.07	0.09	0.82	0.35	0.22	121	35	6.3	506
0	-2	0	3	0.90	0.09	1.72	0.21	0.14	--	32	9.7	325
0	0	-2	3	6.63	0.08	0.89	0.34	0.23	145	24	5.7	475
0	0	0	12	7.22	0.06	0.86	0.41	0.24	171	35	7.0	581
0	0	2	3	7.10	0.07	0.95	0.40	0.20	218	42	8.3	567
0	2	0	3	10.67	0.15	0.72	0.37	0.24	79	33	5.4	542
1	-1	-1	4	5.17	0.07	1.29	0.42	0.16	190	26	8.7	425
1	-1	1	4	4.10	0.06	1.32	0.41	0.16	168	30	7.5	494
1	1	-1	4	9.75	0.10	0.74	0.43	0.24	195	29	6.1	544
1	1	1	4	8.60	0.09	0.83	0.42	0.25	202	35	6.8	469
2	-2	-2	6	1.60	0.08	1.81	0.43	0.10	154	29	8.2	325
2	-2	2	6	1.70	0.09	1.80	0.43	0.10	258	57	9.9	375
2	0	0	3	7.10	0.07	0.93	0.63	0.18	235	25	6.9	425
2	2	-2	6	10.17	0.15	0.70	0.56	0.24	221	24	5.2	487
2	2	2	6	10.13	0.15	0.74	0.58	0.21	214	38	7.2	437

Appendix Table 17. Treatment combinations, stubble-root yields, and nutrient concentrations of *A. gayanus* root system on a highly weathered soil from the Colombian Amazon.

Treatment											
L	P	Mic	Rep	Yield	P	K	Ca	Mg	Zn	Cu	Mn
Coded levels			No.	g/pot	---------%---------				-------ppm------		
-2	-2	-2	6	0.87	0.08	1.18	0.11	0.13	154	20.3	288
-2	-2	2	6	0.00	--	--	--	--	--	--	--
-2	0	0	3	10.80	0.07	0.48	0.13	0.10	90	15.2	331
-2	2	-2	6	17.15	0.15	0.38	0.10	0.09	100	12.3	243
-2	2	2	6	17.10	0.15	0.41	0.12	0.09	100	19.6	274
-1	-1	-1	4	7.17	0.05	0.48	0.15	0.10	78	14.0	352
-1	-1	1	4	7.42	0.07	0.58	0.14	0.10	90	18.7	268
-1	1	-1	4	16.07	0.10	0.36	0.13	0.09	76	13.5	273
-1	1	1	4	15.97	0.10	0.37	0.14	0.09	120	14.6	271
0	-2	0	3	1.00	0.10	1.28	0.17	0.19	142	17.6	415
0	0	-2	3	11.40	0.08	0.48	0.18	0.11	67	12.8	340
0	0	0	12	13.83	0.07	0.42	0.18	0.10	96	14.5	342
0	0	2	3	13.30	0.07	0.41	0.18	0.09	194	17.1	341
0	2	0	3	16.60	0.17	0.35	0.15	0.10	100	14.6	277
1	-1	-1	4	8.30	0.06	0.58	0.16	0.09	61	15.9	238
1	-1	1	4	8.07	0.09	0.61	0.17	0.09	73	15.5	235
1	1	-1	4	16.62	0.11	0.36	0.14	0.09	59	11.2	208
1	1	1	4	17.05	0.10	0.37	0.18	0.09	88	14.4	217
2	-2	-2	6	1.08	0.09	1.11	0.35	0.13	94	14.4	293
2	-2	2	6	1.03	0.10	1.12	0.44	0.13	175	20.9	312
2	0	0	3	11.27	0.07	0.53	0.28	0.09	48	15.0	206
1	1	-1	6	13.88	0.18	0.42	0.22	0.10	65	12.4	204
2	2	2	6	13.53	0.17	0.40	0.25	0.10	140	21.1	213

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BIOGRAPHICAL SKETCH

Pablo E. Mendoza was born at El Banco, Magdalena, Colombia, on June 12, 1944.

In December 1969, he received the degree of Ingeniero Agronomo from the Universidad Nacional, Bogota, Colombia. In January 1968, he started working as agronomist, while conducting his Ingeniero's thesis, in the National Program of Pastures and Forages of the Instituto Colombiano Agropecuario (ICA), a branch of the Colombian Ministry of Agriculture. In September 1972, he was granted a scholarship and a leave of absence by ICA to pursue study towards the Master of Science degree in agriculture, which he received in June 1974 from the University of Florida. He returned to Colombia and worked as Agronomic Researcher for the National Program of Dairy Cattle of ICA stationed at Bogota, with some involvement in teaching and extension until October 1975. In that month, he started serving as director of the National Program of Pastures and Forages which was his last title.

In September 1976, he was granted a scholarship by the Rockefeller Foundation, and a leave of absence by ICA to pursue a Doctor of Philosophy degree in the Agronomy Department for which he is currently a candidate.

The author is a member of the American Society of Agronomy and the Soil Science Society of America. He married the former Kyrina Crespo and they have two children, Pablo E., Jr., and Sara.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

G O Mott

G.O. Mott, Chairman
Professor of Agronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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